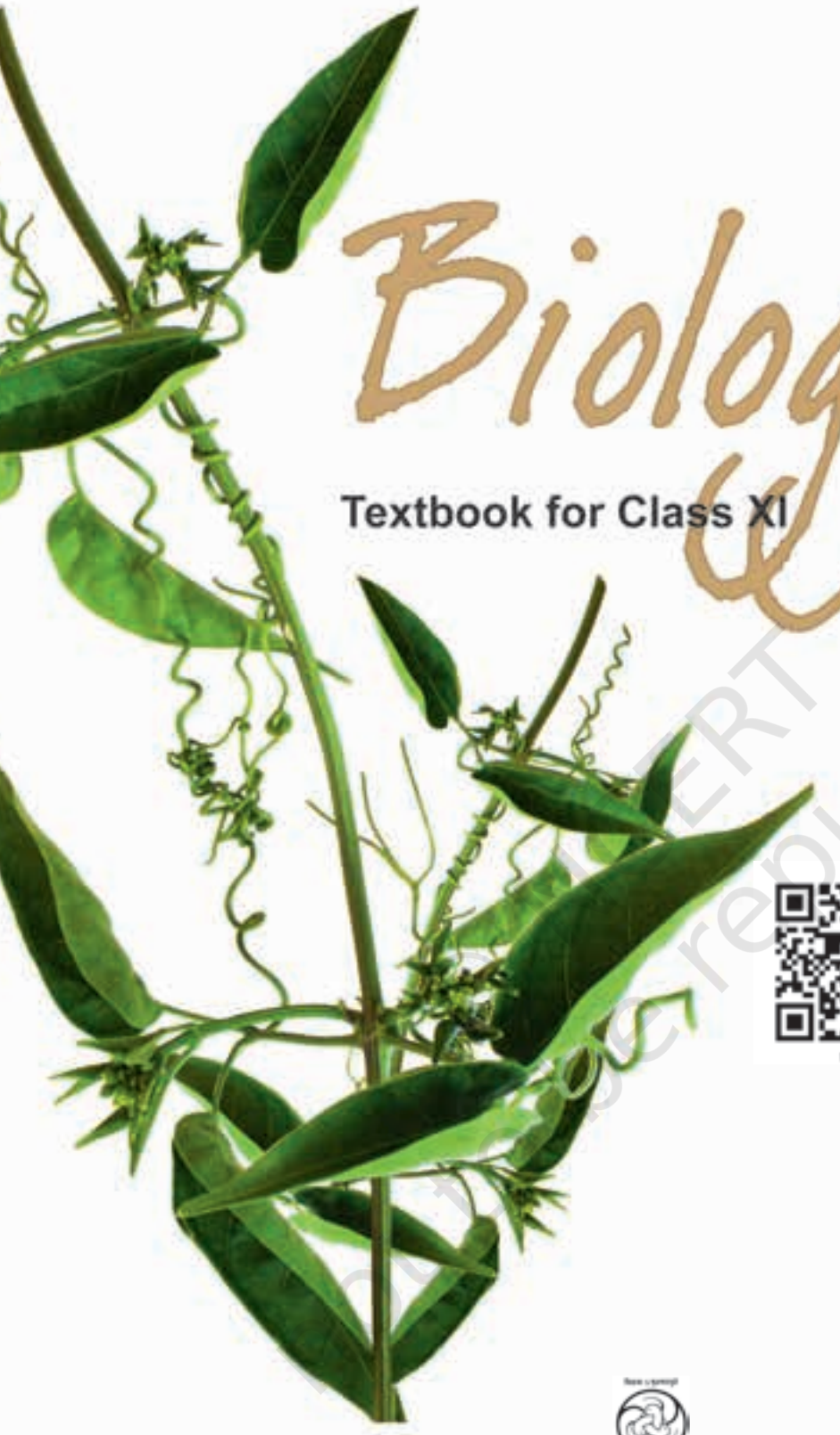

Biology

Textbook for Class XI

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Foreword

The National Curriculum Framework (NCF) 2005, recommends that children's life at school must be linked to their life outside the school. This principle marks a departure from the legacy of bookish learning which continues to shape our system and causes a gap between the school, home and community. The syllabi and textbooks developed on the basis of NCF signify an attempt to implement this basic idea. They also attempt to discourage rote learning and the maintenance of sharp boundaries between different subject areas. We hope these measures will take us significantly further in the direction of a child-centred system of education outlined in the National Policy on Education (1986).

The success of this effort depends on the steps that school principals and teachers will take to encourage children to reflect on their own learning and to pursue imaginative activities and questions. We must recognise that, given space, time and freedom, children generate new knowledge by engaging with the information passed on to them by adults. Treating the prescribed textbook as the sole basis of examination is one of the key reasons why other resources and sites of learning are ignored. Inculcating creativity and initiative is possible if we perceive and treat children as participants in learning, not as receivers of a fixed body of knowledge.

These aims imply considerable change in school routines and mode of functioning. Flexibility in the daily time-table is as necessary as rigour in implementing the annual calendar so that the required number of teaching days are actually devoted to teaching. The methods used for teaching and evaluation will also determine how effective this textbook proves for making children's life at school a happy experience, rather than a source of stress or boredom. Syllabus designers have tried to address the problem of curricular burden by restructuring and reorienting knowledge at different stages with greater consideration for child psychology and the time available for teaching. The textbook attempts to enhance this endeavour by giving higher priority and space to opportunities for contemplation and wondering, discussion in small groups, and activities requiring hands-on experience.

The National Council of Educational Research and Training (NCERT) appreciates the hard work done by the textbook development committee responsible for this book. We wish to thank the Chairperson of the advisory group in science and mathematics, Professor J.V. Narlikar and the Chief Advisor for this book, Professor K. Muralidhar, Department of Zoology, University of Delhi, Delhi for guiding the work of this committee.

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Several teachers contributed to the development of this textbook. We are grateful to their principals for making this possible. We are indebted to the institutions and organisations which have generously permitted us to draw upon their resources, material and personnel. We are especially grateful to the members of the National Monitoring Committee, appointed by the Department of Secondary and Higher Education, Ministry of Human Resource Development under the Chairpersonship of Professor Mrinal Miri and Professor G.P. Deshpande, for their valuable time and contribution.

As an organisation committed to systemic reform and continuous improvement in the quality of its products, NCERT welcomes comments and suggestions which will enable us to undertake further revision and refinement.

Director
National Council of Educational
Research and Training

New Delhi
20 December 2005

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Rationalisation of Content in the Textbook

In view of the COVID-19 pandemic, it is imperative to reduce content load on students. The National Education Policy 2020, also emphasises reducing the content load and providing opportunities for experiential learning with creative mindset. In this background, the NCERT has undertaken the exercise to rationalise the textbooks across all classes. Learning Outcomes already developed by the NCERT across classes have been taken into consideration in this exercise.

Contents of the textbooks have been rationalised in view of the following:

- Overlapping with similar content included in other subject areas in the same class
- Similar content included in the lower or higher class in the same subject
- Difficulty level
- Content, which is easily accessible to students without much interventions from teachers and can be learned by children through self-learning or peer-learning
- Content, which is irrelevant in the present context

This present edition, is a reformatted version after carrying out the changes given above.

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THE CONSTITUTION OF INDIA

PREAMBLE

WE, THE PEOPLE OF INDIA, having solemnly resolved to constitute India into a [1]**[SOVEREIGN SOCIALIST SECULAR DEMOCRATIC REPUBLIC]** and to secure to all its citizens :

JUSTICE, social, economic and political;

LIBERTY of thought, expression, belief, faith and worship;

EQUALITY of status and of opportunity; and to promote among them all

FRATERNITY assuring the dignity of the individual and the [2][unity and integrity of the Nation];

IN OUR CONSTITUENT ASSEMBLY this twenty-sixth day of November, 1949 do **HEREBY ADOPT, ENACT AND GIVE TO OURSELVES THIS CONSTITUTION.**

---

1. Subs. by the Constitution (Forty-second Amendment) Act, 1976, Sec.2, for "Sovereign Democratic Republic" (w.e.f. 3.1.1977)
2. Subs. by the Constitution (Forty-second Amendment) Act, 1976, Sec.2, for "Unity of the Nation" (w.e.f. 3.1.1977)

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A Note for the Teachers and Students

Biology is the science of life. It is the story of life on earth. It is the science of life forms and living processes. Biological systems, often appear to challenge physical laws that govern the behaviour of matter and energy in our world. Historically, biological knowledge was ancillary to knowledge of human body and its function. The latter as we know, is the basis of medical practice. However, parts of biological knowledge developed independent of human application. Fundamental questions about origin of life, the origin and growth of biodiversity, the evolution of flora and fauna of different habitats, etc., caught the imagination of biologists.

The very description of living organisms, be it from morphological perspective, physiological perspective, taxonomical perspective, etc., engaged scientists to such an extent that for sheer convenience, if not for anything else, the subject matter got artificially divided into the sub-disciplines of botany and zoology and later into even microbiology. Meanwhile, physical sciences made heavy inroads into biology, and established biochemistry and biophysics as new sub-disciplines of biology. Mendel's work and its rediscovery in the early twentieth century led to the promotion of study of genetics. The discovery of the double-helical structure of DNA and the deciphering of three dimensional structures of many macromolecules led to the establishment of and phenomenal growth in the dominating area of molecular biology. In a sense, functional disciplines laying emphasis on mechanisms underlying living processes, received more attention, support, intellectual and social recognition. Biology, unfortunately, got divided into classical and modern biology. To the majority of practising biologists, pursuit of biological research became more empirical rather than a curiosity and hypothesis driven intellectual exercise as is the case with theoretical physics, experimental physics, structural chemistry and material science. Fortunately and quietly, general unifying principles of biology were also being discovered, rediscovered and emphasised. The work of Mayr, Dobhzhansky, Haldane, Perutz, Khorana, Morgan, Darlington, Fisher and many others brought respect and seriousness to both classical and molecular biological disciplines. Ecology and Systems biology got established as unifying biological disciplines. Every area of biology began developing interface with not only other areas of biology but also other disciplines of science and mathematics. Pretty soon, the boundaries became porous. They are now on the verge of disappearing altogether. Progress in human biology, biomedical sciences, especially the structure, functioning and evolution of human brain brought in respect, awe and philosophical insights to biology. Biology even stepped out of laboratories, museums and natural parks and raised social, economic and cultural issues capturing the imagination of general public and hence political attention. Educationists did not lag behind and realised that biology should be taught as an interdisciplinary and integrating science at all stages of educational training especially at school and undergraduate levels. A new synthesis of all areas of basic and applied areas of biology is the need of the hour. Biology has come of age. It has an independent set of concepts which are universal just like physics and chemistry and mathematics.

The present volume is the first time presentation of the integrated biology for the school level children. One of the lacunae in biology teaching and study is the absence of integration

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with other disciplinary knowledge of physics, chemistry etc. Further many processes in plants, animals and microbes are similar when looked from physico-chemical perspective. Cell biology has brought out the unifying common cellular level activities underlying apparently diverse phenomena across plants, animals and microbes. Similarly, molecular science (e.g. biochemistry or molecular biology) has revealed the similar molecular mechanisms in all these apparently diverse organisms like plants, animals and microbes. Phenomena like respiration, metabolism, energy utlisation, growth, reproduction and development can be discussed in a unifying manner rather than as separate unrelated processes in plants and animals. An attempt has been made to unify such diverse disciplines in the book. The integration achieved however, is partial and not complete. Hopefully along with changes in the teaching and learning context, to be brought out in the next few years, the next edition of this book will reveal more integration of botany, zoology and microbiology and truly reflect the true nature of biology – the future science of man by man and for man.

This new textbook of Biology for class XI is a completely rewritten book in view of the syllabus revision and restructuring. It is also in accordance with the spirit of the National Curriculum Framework (2005) guidelines. The subject matter is presented under twenty-two chapters which are grouped under five thematic units. Each unit has a brief write up preceding the unit highlighting the essence of the chapters to follow under that unit. Each unit also has a biographical sketch of a prominent scientist in that area. Each chapter has, on the first page, a detailed table of contents giving sub-headings within the chapter. Decimal system using arabic numerals has been employed to indicate these sub-headings. At the end of each chapter a brief summary is provided. This brings to the notice of the student, what she/he is supposed to have learnt by studying the chapter. A set of questions is also provided at the conclusion of each chapter. These questions are essentially to enable the student to test herself/himself as to how much she/he has understood the subject matter. There are questions which are purely of information recall type; there are questions which need analytical thinking to answer and hence test true understanding; there are questions which are problems to solve and finally there are questions which need analysis and speculation as there is no one to answer to such questions. This tests the critical understanding of the subject matter in the mind of the student.

Special emphasis has been given on the narrative style, illustrations, activity exercises, clarity of expression, coverage of topics within the available time in school. A large number of extremely talented and dedicated people including practising teachers helped in bringing out this beautiful book. Our main purpose was to make sure that school level biology is not a burden for students and teachers. We sincerely wish that teaching biology and learning biology would become an enjoyable activity.

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University of Delhi

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UNIT 1

DIVERSITY IN THE LIVING WORLD

Chapter 1
The Living World

Chapter 2
Biological Classification

Chapter 3
Plant Kingdom

Chapter 4
Animal Kingdom

Biology is the science of life forms and living processes. The living world comprises an amazing diversity of living organisms. Early man could easily perceive the difference between inanimate matter and living organisms. Early man deified some of the inanimate matter (wind, sea, fire etc.) and some among the animals and plants. A common feature of all such forms of inanimate and animate objects was the sense of awe or fear that they evoked. The description of living organisms including human beings began much later in human history. Societies which indulged in anthropocentric view of biology could register limited progress in biological knowledge. Systematic and monumental description of life forms brought in, out of necessity, detailed systems of identification, nomenclature and classification. The biggest spin off of such studies was the recognition of the sharing of similarities among living organisms both horizontally and vertically. That all present day living organisms are related to each other and also to all organisms that ever lived on this earth, was a revelation which humbled man and led to cultural movements for conservation of biodiversity. In the following chapters of this unit, you will get a description, including classification, of animals and plants from a taxonomist's perspective.

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Ernst Mayr
(1904 – 2004)

Born on 5 July 1904, in Kempten, Germany, ERNST MAYR, the Harvard University evolutionary biologist who has been called 'The Darwin of the 20th century', was one of the 100 greatest scientists of all time. Mayr joined Harvard's Faculty of Arts and Sciences in 1953 and retired in 1975, assuming the title *Alexander Agassiz Professor of Zoology Emeritus*. Throughout his nearly 80-year career, his research spanned ornithology, taxonomy, zoogeography, evolution, systematics, and the history and philosophy of biology. He almost single-handedly made the origin of species diversity the central question of evolutionary biology that it is today. He also pioneered the currently accepted definition of a biological species. Mayr was awarded the three prizes widely regarded as the *triple crown* of biology: the *Balzan Prize* in 1983, the *International Prize for Biology* in 1994, and the *Crafoord Prize* in 1999. Mayr died at the age of 100 in the year 2004.

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Chapter 1
The Living World

1.1 *Diversity in the Living World*
1.2 *Taxonomic Categories*

How wonderful is the living world! The wide range of living types is amazing. The extraordinary habitats in which we find living organisms, be it cold mountains, deciduous forests, oceans, fresh water lakes, deserts or hot springs, leave us speechless. The beauty of a galloping horse, of the migrating birds, the valley of flowers or the attacking shark evokes awe and a deep sense of wonder. The ecological conflict and cooperation among members of a population and among populations of a community or even the molecular traffic inside a cell make us deeply reflect on – what indeed is life? This question has two implicit questions within it. The first is a technical one and seeks answer to what living is as opposed to the non-living, and the second is a philosophical one, and seeks answer to what the purpose of life is. As scientists, we shall not attempt answering the second question. We will try to reflect on – what is living?

1.1 Diversity in the Living World

If you look around you will see a large variety of living organisms, be it potted plants, insects, birds, your pets or other animals and plants. There are also several organisms that you cannot see with your naked eye but they are all around you. If you were to increase the area that you make observations in, the range and variety of organisms that you see would increase. Obviously, if you were to visit a dense forest, you would probably see a much greater number and kinds of living organisms in it. Each different kind of plant, animal or organism that you see, represents a species. The number of species that are known and described range between 1.7-1.8 million. This refers to **biodiversity** or the number and

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types of organisms present on earth. We should remember here that as we explore new areas, and even old ones, new organisms are continuously being identified.

As stated earlier, there are millions of plants and animals in the world; we know the plants and animals in our own area by their local names. These local names would vary from place to place, even within a country. Probably you would recognise the confusion that would be created if we did not find ways and means to talk to each other, to refer to organisms we are talking about.

Hence, there is a need to standardise the naming of living organisms such that a particular organism is known by the same name all over the world. This process is called **nomenclature**. Obviously, nomenclature or naming is only possible when the organism is described correctly and we know to what organism the name is attached to. This is **identification.**

In order to facilitate the study, number of scientists have established procedures to assign a scientific name to each known organism. This is acceptable to biologists all over the world. For plants, scientific names are based on agreed principles and criteria, which are provided in International Code for Botanical Nomenclature (ICBN). You may ask, how are animals named? Animal taxonomists have evolved International Code of Zoological Nomenclature (ICZN). The scientific names ensure that each organism has only one name. Description of any organism should enable the people (in any part of the world) to arrive at the same name. They also ensure that such a name has not been used for any other known organism.

Biologists follow universally accepted principles to provide scientific names to known organisms. Each name has two components – the **Generic name** and the **specific epithet**. This system of providing a name with two components is called **Binomial nomenclature**. This naming system given by Carolus Linnaeus is being practised by biologists all over the world. This naming system using a two word format was found convenient. Let us take the example of mango to understand the way of providing scientific names better. The scientific name of mango is written as *Mangifera indica*. Let us see how it is a binomial name. In this name *Mangifera* represents the genus while *indica,* is a particular species, or a specific epithet. Other universal rules of nomenclature are as follows:

1. Biological names are generally in Latin and written in italics. They are Latinised or derived from Latin irrespective of their origin.
2. The first word in a biological name represents the genus while the second component denotes the specific epithet.
3. Both the words in a biological name, when handwritten, are separately underlined, or printed in italics to indicate their Latin origin.

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4. The first word denoting the genus starts with a capital letter while the specific epithet starts with a small letter. It can be illustrated with the example of *Mangifera indica*.

Name of the author appears after the specific epithet, i.e., at the end of the biological name and is written in an abbreviated form, e.g., *Mangifera indica* Linn. It indicates that this species was first described by Linnaeus.

Since it is nearly impossible to study all the living organisms, it is necessary to devise some means to make this possible. This process is **classification**. Classification is the process by which anything is grouped into convenient categories based on some easily observable characters. For example, we easily recognise groups such as plants or animals or dogs, cats or insects. The moment we use any of these terms, we associate certain characters with the organism in that group. What image do you see when you think of a dog ? Obviously, each one of us will see 'dogs' and not 'cats'. Now, if we were to think of 'Alsatians' we know what we are talking about. Similarly, suppose we were to say 'mammals', you would, of course, think of animals with external ears and body hair. Likewise, in plants, if we try to talk of 'Wheat', the picture in each of our minds will be of wheat plants, not of rice or any other plant. Hence, all these - 'Dogs', 'Cats', 'Mammals', 'Wheat', 'Rice', 'Plants', 'Animals', etc., are convenient categories we use to study organisms. The scientific term for these categories is **taxa**. Here you must recognise that taxa can indicate categories at very different levels. 'Plants' – also form a taxa. 'Wheat' is also a taxa. Similarly, 'animals', 'mammals', 'dogs' are all taxa – but you know that a dog is a mammal and mammals are animals. Therefore, 'animals', 'mammals' and 'dogs' represent taxa at different levels.

Hence, based on characteristics, all living organisms can be classified into different taxa. This process of classification is **taxonomy**. External and internal structure, along with the structure of cell, development process and ecological information of organisms are essential and form the basis of modern taxonomic studies.

Hence, characterisation, identification, classification and nomenclature are the processes that are basic to taxonomy.

Taxonomy is not something new. Human beings have always been interested in knowing more and more about the various kinds of organisms, particularly with reference to their own use. In early days, human beings needed to find sources for their basic needs of food, clothing and shelter. Hence, the earliest classifications were based on the 'uses' of various organisms.

Human beings were, since long, not only interested in knowing more about different kinds of organisms and their diversities, but also the relationships among them. This branch of study was referred to as **systematics**. The word systematics is derived from the Latin word 'systema' which means systematic arrangement of organisms. Linnaeus

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used *Systema Naturae* as the title of his publication. The scope of systematics was later enlarged to include identification, nomenclature and classification. Systematics takes into account evolutionary relationships between organisms.

1.2 TAXONOMIC CATEGORIES

Classification is not a single step process but involves hierarchy of steps in which each step represents a rank or category. Since the category is a part of overall taxonomic arrangement, it is called the **taxonomic category** and all categories together constitute the **taxonomic hierarchy**. Each category, referred to as a unit of classification, in fact, represents a rank and is commonly termed as **taxon** (pl.: taxa).

Taxonomic categories and hierarchy can be illustrated by an example. Insects represent a group of organisms sharing common features like three pairs of jointed legs. It means insects are recognisable concrete objects which can be classified, and thus were given a rank or category. Can you name other such groups of organisms? Remember, groups represent category. Category further denotes rank. Each rank or *taxon*, in fact, represents a unit of classification. These taxonomic groups/ categories are distinct biological entities and not merely morphological aggregates.

Taxonomical studies of all known organisms have led to the development of common categories such as kingdom, phylum or division (for plants), class, order, family, genus and species. All organisms, including those in the plant and animal kingdoms have species as the lowest category. Now the question you may ask is, how to place an organism in various categories? The basic requirement is the knowledge of characters of an individual or group of organisms. This helps in identifying similarities and dissimilarities among the individuals of the same kind of organisms as well as of other kinds of organisms.

1.2.1 Species

Taxonomic studies consider a group of individual organisms with fundamental similarities as a **species**. One should be able to distinguish one species from the other closely related species based on the distinct morphological differences. Let us consider *Mangifera indica*, *Solanum tuberosum* (potato) and *Panthera leo* (lion). All the three names, *indica, tuberosum* and *leo,* represent the specific epithets, while the first words *Mangifera, Solanum* and *Panthera* are genera and represents another higher level of taxon or category. Each genus may have one or more than one specific epithets representing different organisms, but having morphological similarities. For example, *Panthera* has another specific epithet called *tigris* and *Solanum* includes species like *nigrum* and

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melongena. Human beings belong to the species *sapiens* which is grouped in the genus *Homo*. The scientific name thus, for human being, is written as *Homo sapiens*.

1.2.2 Genus

Genus comprises a group of related species which has more characters in common in comparison to species of other genera. We can say that genera are aggregates of closely related species. For example, potato and brinjal are two different species but both belong to the genus *Solanum*. Lion (*Panthera leo*), leopard (*P. pardus*) and tiger (*P. tigris*) with several common features, are all species of the genus *Panthera*. This genus differs from another genus *Felis* which includes cats.

1.2.3 Family

The next category, **Family**, has a group of related genera with still less number of similarities as compared to genus and species. Families are characterised on the basis of both vegetative and reproductive features of plant species. Among plants for example, three different genera *Solanum*, *Petunia* and *Datura* are placed in the family Solanaceae. Among animals for example, genus *Panthera*, comprising lion, tiger, leopard is put along with genus, *Felis* (cats) in the family Felidae. Similarly, if you observe the features of a cat and a dog, you will find some similarities and some differences as well. They are separated into two different families – Felidae and Canidae, respectively.

1.2.4 Order

You have seen earlier that categories like species, genus and families are based on a number of similar characters. Generally, order and other higher taxonomic categories are identified based on the aggregates of characters. Order being a higher category, is the assemblage of families which exhibit a few similar characters. The similar characters are less in number as compared to different genera included in a family. Plant families like Convolvulaceae, Solanaceae are included in the order Polymoniales mainly based on the floral characters. The animal order, Carnivora, includes families like Felidae and Canidae.

1.2.5 Class

This category includes related orders. For example, order Primata comprising monkey, gorilla and gibbon is placed in class Mammalia along with order Carnivora that includes animals like tiger, cat and dog. Class Mammalia has other orders also.

1.2.6 Phylum

Classes comprising animals like fishes, amphibians, reptiles, birds along with mammals constitute the next higher category called Phylum. All

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these, based on the common features like presence of notochord and dorsal hollow neural system, are included in phylum Chordata. In case of plants, classes with a few similar characters are assigned to a higher category called Division.

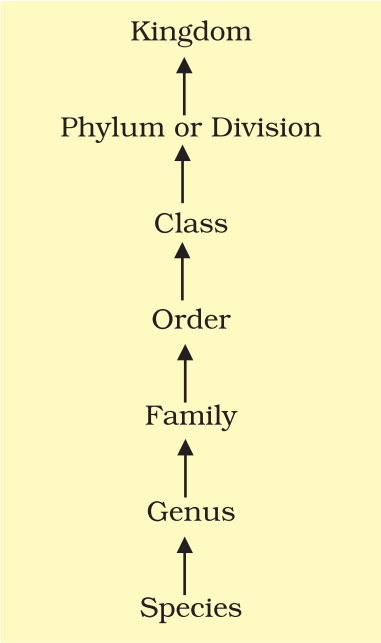

Figure 1.1 Taxonomic categories showing hierarchial arrangement in ascending order

1.2.7 Kingdom

All animals belonging to various phyla are assigned to the highest category called Kingdom Animalia in the classification system of animals. The Kingdom Plantae, on the other hand, is distinct, and comprises all plants from various divisions. Henceforth, we will refer to these two groups as animal and plant kingdoms.

The taxonomic categories from species to kingdom have been shown in ascending order starting with species in Figure 1.1. These are broad categories. However, taxonomists have also developed sub-categories in this hierarchy to facilitate more sound and scientific placement of various taxa.

Look at the hierarchy in Figure 1.1. Can you recall the basis of arrangement? Say, for example, as we go higher from species to kingdom, the number of common characteristics goes on decreasing. Lower the taxa, more are the characteristics that the members within the taxon share. Higher the category, greater is the difficulty of determining the relationship to other taxa at the same level. Hence, the problem of classification becomes more complex.

Table 1.1 indicates the taxonomic categories to which some common organisms like housefly, man, mango and wheat belong.

TABLE 1.1 Organisms with their Taxonomic Categories

Common Name	Biological Name	Genus	Family	Order	Class	Phylum/ Division
Man	*Homo sapiens*	*Homo*	Hominidae	Primata	Mammalia	Chordata
Housefly	*Musca domestica*	*Musca*	Muscidae	Diptera	Insecta	Arthropoda
Mango	*Mangifera indica*	*Mangifera*	Anacardiaceae	Sapindales	Dicotyledonae	Angiospermae
Wheat	*Triticum aestivum*	*Triticum*	Poaceae	Poales	Monocotyledonae	Angiospermae

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SUMMARY

The living world is rich in variety. Millions of plants and animals have been identified and described but a large number still remains unknown. The very range of organisms in terms of size, colour, habitat, physiological and morphological features make us seek the defining characteristics of living organisms. In order to facilitate the study of kinds and diversity of organisms, biologists have evolved certain rules and principles for identification, nomenclature and classification of organisms. The branch of knowledge dealing with these aspects is referred to as taxonomy. The taxonomic studies of various species of plants and animals are useful in agriculture, forestry, industry and in general for knowing our bio-resources and their diversity. The basics of taxonomy like identification, naming and classification of organisms are universally evolved under international codes. Based on the resemblances and distinct differences, each organism is identified and assigned a correct scientific/biological name comprising two words as per the binomial system of nomenclature. An organism represents/occupies a place or position in the system of classification. There are many categories/ ranks which are generally referred to as taxonomic categories or taxa. All the categories constitute a taxonomic hierarchy.

EXERCISES

1. Why are living organisms classified?
2. Why are the classification systems changing every now and then?
3. What different criteria would you choose to classify people that you meet often?
4. What do we learn from identification of individuals and populations?
5. Given below is the scientific name of Mango. Identify the correctly written name.
   Mangifera Indica
   Mangifera indica
6. Define a taxon. Give some examples of taxa at different hierarchical levels.
7. Can you identify the correct sequence of taxonomical categories?
   (a) Species → Order → Phylum → Kingdom
   (b) Genus → Species → Order → Kingdom
   (c) Species → Genus → Order → Phylum
8. Try to collect all the currently accepted meanings for the word 'species'. Discuss with your teacher the meaning of species in case of higher plants and animals on one hand, and bacteria on the other hand.
9. Define and understand the following terms:
   (i) Phylum (ii) Class (iii) Family (iv) Order (v) Genus
10. Illustrate the taxonomical hierarchy with suitable examples of a plant and an animal.

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Chapter 2
Biological Classification

2.1 Kingdom Monera
2.2 Kingdom Protista
2.3 Kingdom Fungi
2.4 Kingdom Plantae
2.5 Kingdom Animalia
2.6 Viruses, Viroids and Lichens

Since the dawn of civilisation, there have been many attempts to classify living organisms. It was done instinctively not using criteria that were scientific but borne out of a need to use organisms for our own use – for food, shelter and clothing. Aristotle was the earliest to attempt a more scientific basis for classification. He used simple morphological characters to classify plants into trees, shrubs and herbs. He also divided animals into two groups, those which had red blood and those that did not.

In Linnaeus' time a **Two Kingdom** system of classification with **Plantae** and **Animalia** kingdoms was developed that included all plants and animals respectively. This system did not distinguish between the eukaryotes and prokaryotes, unicellular and multicellular organisms and photosynthetic (green algae) and non-photosynthetic (fungi) organisms. Classification of organisms into plants and animals was easily done and was easy to understand, but, a large number of organisms did not fall into either category. Hence the two kingdom classification used for a long time was found inadequate. Besides, gross morphology a need was also felt for including other characteristics like cell structure, nature of wall, mode of nutrition, habitat, methods of reproduction, evolutionary relationships, etc. Classification systems for the living organisms have hence, undergone several changes over the time. Though plant and animal kingdoms have been a constant under all different systems, the understanding of what groups/organisms be included under these kingdoms have been changing; the number and nature of other kingdoms have also been understood differently by different scientists over the time.

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TABLE 2.1 Characteristics of the Five Kingdoms

Characters	Five Kingdoms				
	Monera	**Protista**	**Fungi**	**Plantae**	**Animalia**
Cell type	Prokaryotic	Eukaryotic	Eukaryotic	Eukaryotic	Eukaryotic
Cell wall	Noncellulosic (Polysaccharide + amino acid)	Present in some	Present with chitin	Present (cellulose)	Absent
Nuclear membrane	Absent	Present	Present	Present	Present
Body organisation	Cellular	Cellular	Multiceullar/ loose tissue	Tissue/ organ	Tissue/organ/ organ system
Mode of nutrition	Autotrophic (chemosynthetic and photosynthetic) and Heterotrophic (saprophytic/parasitic)	Autotrophic (Photosynthetic) and Heterotrophic	Heterotrophic (Saprophytic/ Parasitic)	Autotrophic (Photosynthetic)	Heterotrophic (Holozoic/ Saprophytic etc.)

R.H. Whittaker (1969) proposed a **Five Kingdom Classification.** The kingdoms defined by him were named **Monera, Protista, Fungi, Plantae** and **Animalia.** The main criteria for classification used by him include cell structure, body organisation, mode of nutrition, reproduction and phylogenetic relationships. Table 2.1 gives a comparative account of different characteristics of the five kingdoms.

The three-domain system has also been proposed that divides the Kingdom Monera into two domains, leaving the remaining eukaryotic kingdoms in the third domain and thereby a six kingdom classification. You will learn about this system in detail in higher classes.

Let us look at this five kingdom classification to understand the issues and considerations that influenced the classification system. Earlier classification systems included bacteria, blue green algae, fungi, mosses, ferns, gymnosperms and the angiosperms under 'Plants'. The character that unified this whole kingdom was that all the organisms included had a cell wall in their cells. This placed together groups which widely differed in other characteristics. It brought together the prokaryotic bacteria and the blue green algae (cyanobacteria) with other groups which were eukaryotic. It also grouped together the unicellular organisms and the multicellular ones, say, for example, *Chlamydomonas* and *Spirogyra* were placed together under algae. The classification did not differentiate between the heterotrophic group – fungi, and the autotrophic green plants, though they also showed a characteristic difference in their walls composition – the fungi had chitin

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in their walls while the green plants had a cellulosic cell wall. When such characteristics were considered, the fungi were placed in a separate kingdom – Kingdom Fungi. All prokaryotic organisms were grouped together under Kingdom Monera and the unicellular eukaryotic organisms were placed in Kingdom Protista. Kingdom Protista has brought together *Chlamydomonas, Chlorella* (earlier placed in Algae within Plants and both having cell walls) with *Paramoecium* and *Amoeba* (which were earlier placed in the animal kingdom which lack cell wall). It has put together organisms which, in earlier classifications, were placed in different kingdoms. This happened because the criteria for classification changed. This kind of changes will take place in future too depending on the improvement in our understanding of characteristics and evolutionary relationships. Over time, an attempt has been made to evolve a classification system which reflects not only the morphological, physiological and reproductive similarities, but is also phylogenetic, i.e., is based on evolutionary relationships.

In this chapter we will study characteristics of Kingdoms Monera, Protista and Fungi of the Whittaker system of classification. The Kingdoms Plantae and Animalia, commonly referred to as plant and animal kingdoms, respectively, will be dealt separately in chapters 3 and 4.

2.1 KINGDOM MONERA

Bacteria are the sole members of the Kingdom Monera. They are the most abundant micro-organisms. Bacteria occur almost everywhere. Hundreds of bacteria are present in a handful of soil. They also live in extreme habitats such as hot springs, deserts, snow and deep oceans where very few other life forms can survive. Many of them live in or on other organisms as parasites.

Bacteria are grouped under four categories based on their shape: the spherical Coccus (pl.: cocci), the rod-shaped Bacillus (pl.: bacilli), the comma-shaped Vibrium (pl.: vibrio) and the spiral Spirillum (pl.: spirilla) (Figure 2.1).

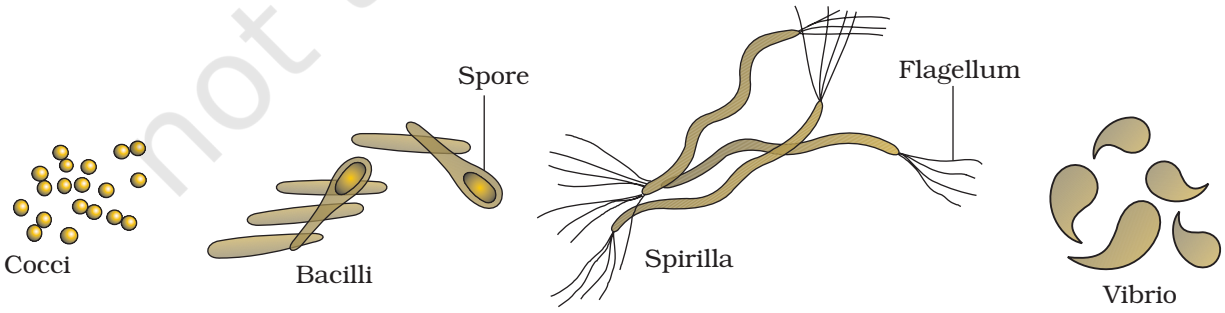

Figure 2.1 Bacteria of different shapes

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Though the bacterial structure is very simple, they are very complex in behaviour. Compared to many other organisms, bacteria as a group show the most extensive metabolic diversity. Some of the bacteria are autotrophic, i.e., they synthesise their own food from inorganic substrates. They may be photosynthetic autotrophic or chemosynthetic autotrophic. The vast majority of bacteria are heterotrophs, i.e., they depend on other organisms or on dead organic matter for food.

2.1.1 Archaebacteria

These bacteria are special since they live in some of the most harsh habitats such as extreme salty areas (halophiles), hot springs (thermoacidophiles) and marshy areas (methanogens). Archaebacteria differ from other bacteria in having a different cell wall structure and this feature is responsible for their survival in extreme conditions. Methanogens are present in the gut of several ruminant animals such as cows and buffaloes and they are responsible for the production of methane (biogas) from the dung of these animals.

2.1.2 Eubacteria

There are thousands of different **eubacteria** or 'true bacteria'. They are characterised by the presence of a rigid cell wall, and if motile, a flagellum. The **cyanobacteria** (also referred to as blue-green algae) have chlorophyll *a* similar to green plants and are **photosynthetic autotrophs** (Figure 2.2). The cyanobacteria are unicellular, colonial or filamentous, freshwater/marine or terrestrial algae. The colonies are generally surrounded by gelatinous sheath. They often form blooms in polluted water bodies. Some of these organisms can fix atmospheric nitrogen in specialised cells called **heterocysts,** e.g., *Nostoc* and *Anabaena*. **Chemosynthetic autotrophic** bacteria oxidise various inorganic substances such as nitrates, nitrites and ammonia and use the released energy for their ATP production. They play a great role in recycling nutrients like nitrogen, phosphorous, iron and sulphur.

Heterotrophic bacteria are most abundant in nature. The majority are important decomposers. Many of them have a significant impact on human affairs. They are helpful in making curd from milk, production of antibiotics, fixing nitrogen in legume

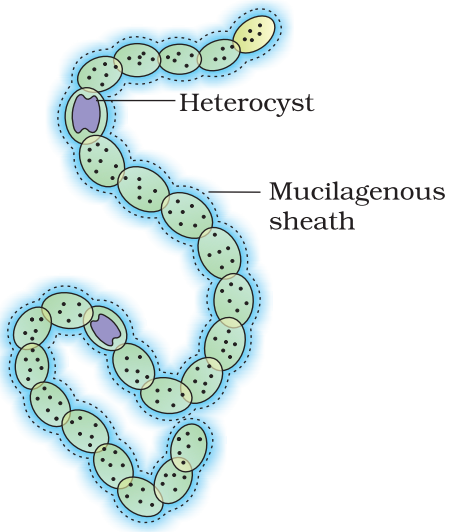

Figure 2.2 A filamentous blue-green algae – *Nostoc*

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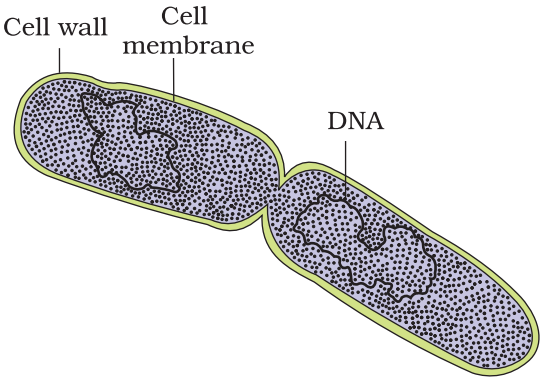

Figure 2.3 A dividing bacterium

roots, etc. Some are pathogens causing damage to human beings, crops, farm animals and pets. Cholera, typhoid, tetanus, citrus canker are well known diseases caused by different bacteria.

Bacteria reproduce mainly by fission (Figure 2.3). Sometimes, under unfavourable conditions, they produce spores. They also reproduce by a sort of sexual reproduction by adopting a primitive type of DNA transfer from one bacterium to the other.

The **Mycoplasma** are organisms that completely lack a cell wall. They are the smallest living cells known and can survive without oxygen. Many mycoplasma are pathogenic in animals and plants.

2.2 KINGDOM PROTISTA

All single-celled eukaryotes are placed under **Protista**, but the boundaries of this kingdom are not well defined. What may be 'a photosynthetic protistan' to one biologist may be 'a plant' to another. In this book we include Chrysophytes, Dinoflagellates, Euglenoids, Slime moulds and Protozoans under Protista. Members of Protista are primarily aquatic. This kingdom forms a link with the others dealing with plants, animals and fungi. Being eukaryotes, the protistan cell body contains a well defined nucleus and other membrane-bound organelles. Some have flagella or cilia. Protists reproduce asexually and sexually by a process involving cell fusion and zygote formation.

2.2.1 Chrysophytes

This group includes diatoms and golden algae (desmids). They are found in fresh water as well as in marine environments. They are microscopic and float passively in water currents (plankton). Most of them are photosynthetic. In diatoms the cell walls form two thin overlapping shells, which fit together as in a soap box. The walls are embedded with silica and thus the walls are indestructible. Thus, diatoms have left behind large amount of cell wall deposits in their habitat; this accumulation over billions of years is referred to as 'diatomaceous earth'. Being gritty this soil is used in polishing, filtration of oils and syrups. Diatoms are the chief 'producers' in the oceans.

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2.2.2 Dinoflagellates

These organisms are mostly marine and photosynthetic. They appear yellow, green, brown, blue or red depending on the main pigments present in their cells. The cell wall has stiff cellulose plates on the outer surface. Most of them have two flagella; one lies longitudinally and the other transversely in a furrow between the wall plates. Very often, red dinoflagellates (Example: *Gonyaulax)* undergo such rapid multiplication that they make the sea appear red (red tides). Toxins released by such large numbers may even kill other marine animals such as fishes.

2.2.3 Euglenoids

Majority of them are fresh water organisms found in stagnant water. Instead of a cell wall, they have a protein rich layer called pellicle which makes their body flexible. They have two flagella, a short and a long one. Though they are photosynthetic in the presence of sunlight, when deprived of sunlight they behave like heterotrophs by predating on other smaller organisms. Interestingly, the pigments of euglenoids are identical to those present in higher plants. Example: *Euglena* (Figure 2.4b).

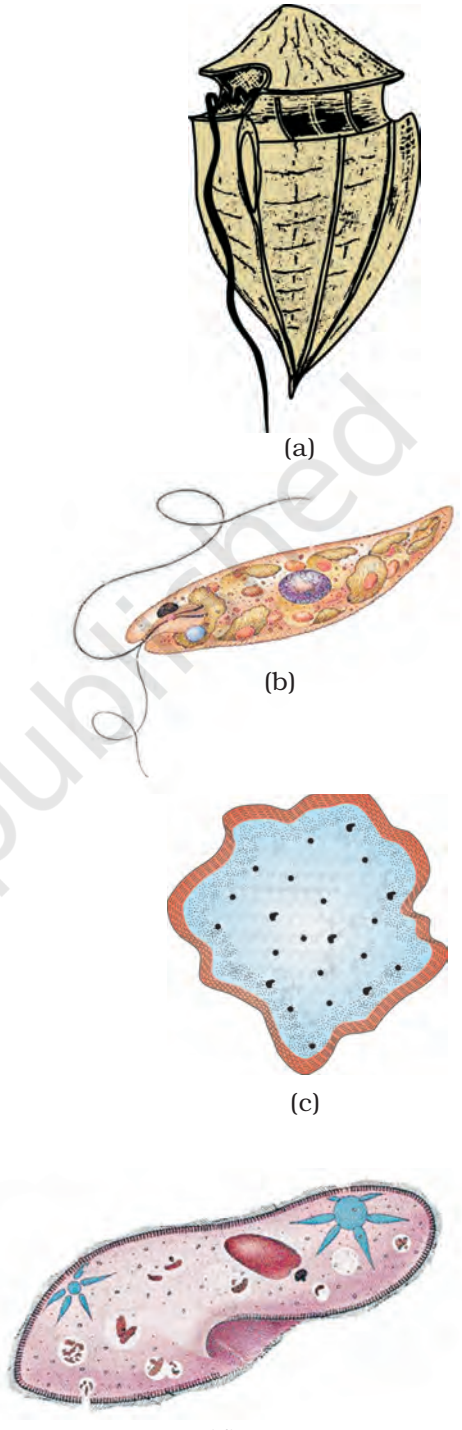
2.2.4 Slime Moulds

Slime moulds are saprophytic protists. The body moves along decaying twigs and leaves engulfing organic material. Under suitable conditions, they form an aggregation called plasmodium which may grow and spread over several feet. During unfavourable conditions, the plasmodium differentiates and forms fruiting bodies bearing spores at their tips. The spores possess true walls. They are extremely resistant and survive for many years, even under adverse conditions. The spores are dispersed by air currents.

2.2.5 Protozoans

All protozoans are heterotrophs and live as predators or parasites. They are believed to be primitive relatives of animals. There are four major groups of protozoans.

Amoeboid protozoans: These organisms live in fresh water, sea water or moist soil. They move and capture



(a) (b) (c) (d)

Figure 2.4 (a) *Dinoflagellates* (b) *Euglena* (c) *Slime mould* (d) *Paramoecium*

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their prey by putting out pseudopodia (false feet) as in *Amoeba*. Marine forms have silica shells on their surface. Some of them such as *Entamoeba* are parasites.

Flagellated protozoans: The members of this group are either free-living or parasitic. They have flagella. The parasitic forms cause diaseases such as sleeping sickness. Example: *Trypanosoma*.

Ciliated protozoans: These are aquatic, actively moving organisms because of the presence of thousands of cilia. They have a cavity (gullet) that opens to the outside of the cell surface. The coordinated movement of rows of cilia causes the water laden with food to be steered into the gullet. Example: *Paramoecium* (Figure 2.4d).

Sporozoans: This includes diverse organisms that have an infectious spore-like stage in their life cycle. The most notorious is *Plasmodium* (malarial parasite) which causes malaria, a disease which has a staggering effect on human population.

2.3 KINGDOM FUNGI

The fungi constitute a unique kingdom of heterotrophic organisms. They show a great diversity in morphology and habitat. You must have seen fungi on a moist bread and rotten fruits. The common mushroom you eat and toadstools are also fungi. White spots seen on mustard leaves are due to a parasitic fungus. Some unicellular fungi, e.g., yeast are used to make bread and beer. Other fungi cause diseases in plants and animals; wheat rust-causing *Puccinia* is an important example. Some are the source of antibiotics, e.g., *Penicillium*. Fungi are cosmopolitan and occur in air, water, soil and on animals and plants. They prefer to grow in warm and humid places. Have you ever wondered why we keep food in the refrigerator ? Yes, it is to prevent food from going bad due to bacterial or fungal infections.

With the exception of yeasts which are unicellular, fungi are filamentous. Their bodies consist of long, slender thread-like structures called hyphae. The network of hyphae is known as mycelium. Some hyphae are continuous tubes filled with multinucleated cytoplasm – these are called coenocytic hyphae. Others have septae or cross walls in their hyphae. The cell walls of fungi are composed of chitin and polysaccharides.

Most fungi are heterotrophic and absorb soluble organic matter from dead substrates and hence are called **saprophytes**. Those that depend on living plants and animals are called **parasites**. They can also live as **symbionts** – in association with algae as **lichens** and with roots of higher plants as **mycorrhiza**.

Reproduction in fungi can take place by vegetative means – fragmentation, fission and budding. Asexual reproduction is by spores

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called conidia or sporangiospores or zoospores, and sexual reproduction is by oospores, ascospores and basidiospores. The various spores are produced in distinct structures called fruiting bodies. The sexual cycle involves the following three steps:

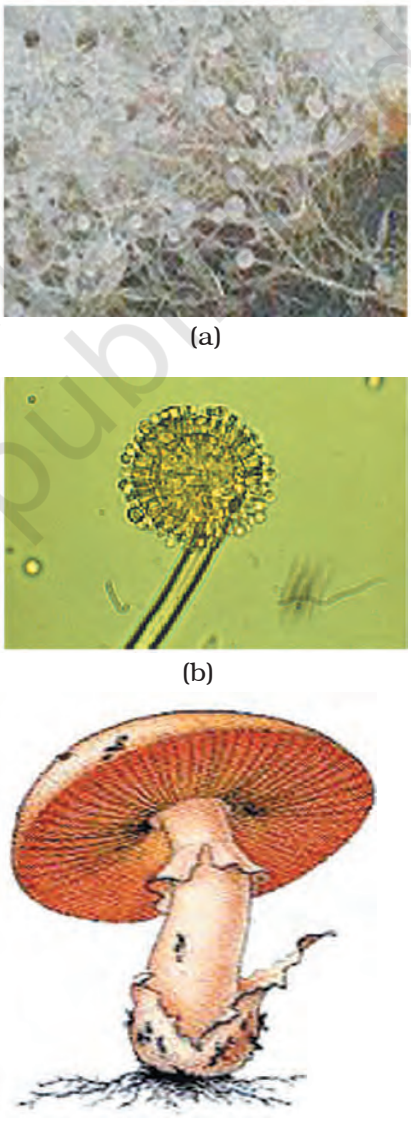
(i) Fusion of protoplasms between two motile or non-motile gametes called **plasmogamy.**

(ii) Fusion of two nuclei called **karyogamy.**

(iii) Meiosis in zygote resulting in haploid spores.

When a fungus reproduces sexually, two haploid hyphae of compatible mating types come together and fuse. In some fungi the fusion of two haploid cells immediately results in diploid cells (2n). However, in other fungi (ascomycetes and basidiomycetes), an intervening dikaryotic stage (n + n, i.e., two nuclei per cell) occurs; such a condition is called a **dikaryon** and the phase is called **dikaryophase** of fungus. Later, the parental nuclei fuse and the cells become diploid. The fungi form fruiting bodies in which reduction division occurs, leading to formation of haploid spores.

The morphology of the mycelium, mode of spore formation and fruiting bodies form the basis for the division of the kingdom into various classes.



(a) (b) (c)

Figure 2.5 Fungi: (a) *Mucor* (b) *Aspergillus* (c) *Agaricus*

2.3.1 Phycomycetes

Members of phycomycetes are found in aquatic habitats and on decaying wood in moist and damp places or as obligate parasites on plants. The mycelium is aseptate and coenocytic. Asexual reproduction takes place by zoospores (motile) or by aplanospores (non-motile). These spores are endogenously produced in sporangium. A zygospore is formed by fusion of two gametes. These gametes are similar in morphology (isogamous) or dissimilar (anisogamous or oogamous). Some common examples are *Mucor* (Figure 2.5a), *Rhizopus* (the bread mould mentioned earlier) and *Albugo* (the parasitic fungi on mustard).

2.3.2 Ascomycetes

Commonly known as sac-fungi, the ascomycetes are mostly multicellular, e.g., *Penicillium*, or rarely unicellular, e.g., yeast (*Saccharomyces*). They are saprophytic, decomposers, parasitic or coprophilous (growing on dung). Mycelium

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is branched and septate. The asexual spores are conidia produced exogenously on the special mycelium called conidiophores. Conidia on germination produce mycelium. Sexual spores are called ascospores which are produced endogenously in sac like asci (singular ascus). These asci are arranged in different types of fruiting bodies called ascocarps. Some examples are *Aspergillus* (Figure 2.5b), *Claviceps* and *Neurospora. Neurospora* is used extensively in biochemical and genetic work. Many members like morels and truffles are edible and are considered delicacies.

2.3.3 Basidiomycetes

Commonly known forms of basidiomycetes are mushrooms, bracket fungi or puffballs. They grow in soil, on logs and tree stumps and in living plant bodies as parasites, e.g., rusts and smuts. The mycelium is branched and septate. The asexual spores are generally not found, but vegetative reproduction by fragmentation is common. The sex organs are absent, but plasmogamy is brought about by fusion of two vegetative or somatic cells of different strains or genotypes. The resultant structure is dikaryotic which ultimately gives rise to basidium. Karyogamy and meiosis take place in the basidium producing four basidiospores. The basidiospores are exogenously produced on the basidium (pl.: basidia). The basidia are arranged in fruiting bodies called basidiocarps. Some common members are *Agaricus* (mushroom) (Figure 2.5c), *Ustilago* (smut) and *Puccinia* (rust fungus).

2.3.4 Deuteromycetes

Commonly known as imperfect fungi because only the asexual or vegetative phases of these fungi are known. When the sexual forms of these fungi were discovered they were moved into classes they rightly belong to. It is also possible that the asexual and vegetative stage have been given one name (and placed under deuteromycetes) and the sexual stage another (and placed under another class). Later when the linkages were established, the fungi were correctly identified and moved out of deuteromycetes. Once perfect (sexual) stages of members of dueteromycetes were discovered, they were often moved to ascomycetes and basidiomycetes. The deuteromycetes reproduce only by asexual spores known as conidia. The mycelium is septate and branched. Some members are saprophytes or parasites while a large number of them are decomposers of litter and help in mineral cycling. Some examples are *Alternaria, Colletotrichum* and *Trichoderma*.

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2.4 KINGDOM PLANTAE

Kingdom Plantae includes all eukaryotic chlorophyll-containing organisms commonly called plants. A few members are partially heterotrophic such as the insectivorous plants or parasites. Bladderwort and Venus fly trap are examples of insectivorous plants and *Cuscuta* is a parasite. The plant cells have an eukaryotic structure with prominent chloroplasts and cell wall mainly made of cellulose. You will study the eukaryotic cell structure in detail in Chapter 8. Plantae includes algae, bryophytes, pteridophytes, gymnosperms and angiosperms.

Life cycle of plants has two distinct phases – the diploid sporophytic and the haploid gametophytic – that alternate with each other. The lengths of the haploid and diploid phases, and whether these phases are free–living or dependent on others, vary among different groups in plants. This phenomenon is called **alternation of generations.** You will study further details of this kingdom in Chapter 3.

2.5 KINGDOM ANIMALIA

This kingdom is characterised by heterotrophic eukaryotic organisms that are multicellular and their cells lack cell walls. They directly or indirectly depend on plants for food. They digest their food in an internal cavity and store food reserves as glycogen or fat. Their mode of nutrition is holozoic – by ingestion of food. They follow a definite growth pattern and grow into adults that have a definite shape and size. Higher forms show elaborate sensory and neuromotor mechanism. Most of them are capable of locomotion.

The sexual reproduction is by copulation of male and female followed by embryological development. Salient features of various phyla are described in Chapter 4.

2.6 VIRUSES, VIROIDS, PRIONS AND LICHENS

In the five kingdom classification of Whittaker there is no mention of lichens and some acellular organisms like viruses, viroids and prions. These are briefly introduced here.

All of us who have suffered the ill effects of common cold or 'flu' know what effects viruses can have on us, even if we do not associate it with our condition. Viruses did not find a place in classification since they are not considered truly 'living', if we understand living as those organisms that have a cell structure. The viruses are non-cellular organisms that are characterised by having an inert crystalline structure outside the living cell.

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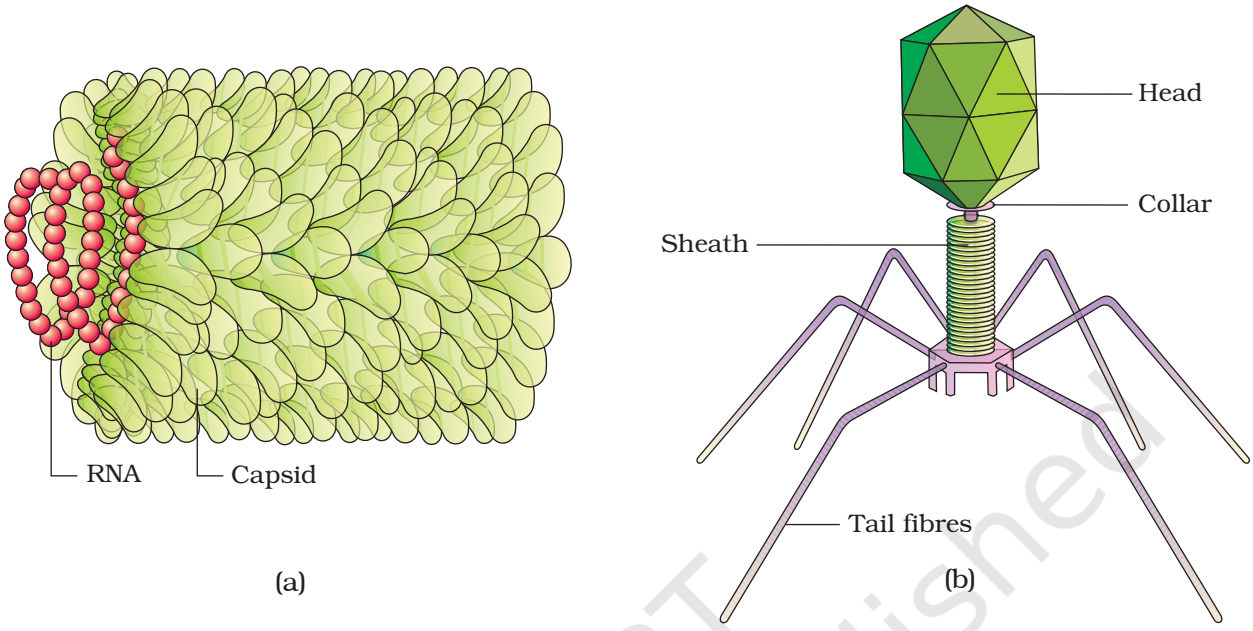

Figure 2.6 (a) Tobacco Mosaic Virus (TMV) (b) Bacteriophage

Once they infect a cell, they take over the machinery of the host cell to replicate themselves, killing the host. Would you call viruses living or non-living?

Virus means venom or poisonous fluid. Dmitri Ivanowsky (1892) recognised certain microbes as causal organism of the mosaic disease of tobacco (Figure 2.6a). These were found to be smaller than bacteria because they passed through bacteria-proof filters. M.W. Beijerinck (1898) demonstrated that the extract of the infected plants of tobacco could cause infection in healthy plants and named the new pathogen "virus" and called the fluid as *Contagium vivum fluidum* (infectious living fluid). W.M. Stanley (1935) showed that viruses could be crystallised and crystals consist largely of proteins. They are inert outside their specific host cell. Viruses are obligate parasites.

In addition to proteins, viruses also contain genetic material, that could be either RNA or DNA. No virus contains both RNA and DNA. A virus is a nucleoprotein and the genetic material is infectious. In general, viruses that infect plants have single stranded RNA and viruses that infect animals have either single or double stranded RNA or double stranded DNA. Bacterial viruses or bacteriophages (viruses that infect the bacteria) are usually double stranded DNA viruses (Figure 2.6b). The protein coat called capsid made of small subunits called capsomeres, protects the nucleic acid. These capsomeres are arranged in helical or polyhedral geometric forms. Viruses cause diseases like mumps, small pox, herpes and influenza. AIDS in humans is also caused by a virus. In plants, the symptoms can be mosaic formation, leaf rolling and curling, yellowing

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and vein clearing, dwarfing and stunted growth.

Viroids : In 1971, T.O. Diener discovered a new infectious agent that was smaller than viruses and caused potato spindle tuber disease. It was found to be a free RNA; it lacked the protein coat that is found in viruses, hence the name viroid. The RNA of the viroid was of low molecular weight.

Prions : In modern medicine certain infectious neurological diseases were found to be transmitted by an agent consisting of abnormally folded protein. The agent was similar in size to viruses. These agents were called prions. The most notable diseases caused by prions are bovine spongiform encephalopathy (BSE) commonly called mad cow disease in cattle and its analogous variant Creutzfeldt–Jacob disease (CJD) in humans.

Lichens : Lichens are symbiotic associations i.e. mutually useful associations, between algae and fungi. The algal component is known as **phycobiont** and fungal component as **mycobiont,** which are autotrophic and heterotrophic, respectively. Algae prepare food for fungi and fungi provide shelter and absorb mineral nutrients and water for its partner. So close is their association that if one saw a lichen in nature one would never imagine that they had two different organisms within them. Lichens are very good pollution indicators – they do not grow in polluted areas.

SUMMARY

Biological classification of plants and animals was first proposed by Aristotle on the basis of simple morphological characters. Linnaeus later classified all living organisms into two kingdoms – Plantae and Animalia. Whittaker proposed an elaborate five kingdom classification – Monera, Protista, Fungi, Plantae and Animalia. The main criteria of the five kingdom classification were cell structure, body organisation, mode of nutrition and reproduction, and phylogenetic relationships.

In the five kingdom classification, bacteria are included in Kingdom Monera. Bacteria are cosmopolitan in distribution. These organisms show the most extensive metabolic diversity. Bacteria may be autotrophic or heterotrophic in their mode of nutrition. Kingdom Protista includes all single-celled eukaryotes such as Chrysophytes, Dinoflagellates, Euglenoids, Slime-moulds and Protozoans. Protists have defined nucleus and other membrane bound organelles. They reproduce both asexually and sexually. Members of Kingdom Fungi show a great diversity in structures and habitat. Most fungi are saprophytic in their mode of nutrition. They show asexual and sexual reproduction. Phycomycetes, Ascomycetes, Basidiomycetes and Deuteromycetes are the four classes under this kingdom. The plantae includes all eukaryotic chlorophyll-containing organisms. Algae, bryophytes, pteridophytes, gymnosperms and angiosperms are included in this group. The life cycle of plants exhibit alternation of generations – gametophytic and sporophytic generations. The heterotrophic eukaryotic, multicellular organisms lacking a cell wall are included in the Kingdom Animalia. The mode of

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EXERCISES

1. Discuss how classification systems have undergone several changes over a period of time?
2. State two economically important uses of:
   (a) heterotrophic bacteria
   (b) archaebacteria
3. What is the nature of cell-walls in diatoms?
4. Find out what do the terms 'algal bloom' and 'red-tides' signify.
5. How are viroids different from viruses?
6. Describe briefly the four major groups of Protozoa.
7. Plants are autotrophic. Can you think of some plants that are partially heterotrophic?
8. What do the terms phycobiont and mycobiont signify?
9. Give a comparative account of the classes of Kingdom Fungi under the following:
   (i) mode of nutrition
   (ii) mode of reproduction
10. What are the characteristic features of Euglenoids?
11. Give a brief account of viruses with respect to their structure and nature of genetic material. Also name four common viral diseases.
12. Organise a discussion in your class on the topic – Are viruses living or non-living?

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Chapter 3
Plant Kingdom

3.1 Algae

3.2 Bryophytes

3.3 Pteridophytes

3.4 Gymnosperms

3.5 Angiosperms

In the previous chapter, we looked at the broad classification of living organisms under the system proposed by Whittaker (1969) wherein he suggested the Five Kingdom classification viz. Monera, Protista, Fungi, Animalia and Plantae. In this chapter, we will deal in detail with further classification within Kingdom Plantae popularly known as the 'plant kingdom'.

We must stress here that our understanding of the plant kingdom has changed over time. Fungi, and members of the Monera and Protista having cell walls have now been excluded from Plantae though earlier classifications placed them in the same kingdom. So, the cyanobacteria that are also referred to as blue green algae are not 'algae' any more. In this chapter, we will describe Algae, Bryophytes, Pteridophytes, Gymnosperms and Angiosperms under Plantae.

Let us also look at classification within angiosperms to understand some of the concerns that influenced the classification systems. The earliest systems of classification used only gross superficial morphological characters such as habit, colour, number and shape of leaves, etc. They were based mainly on vegetative characters or on the androecium structure (system given by Linnaeus). Such systems were **artificial;** they separated the closely related species since they were based on a few characteristics. Also, the artificial systems gave equal weightage to vegetative and sexual characteristics; this is not acceptable since we know that often the vegetative characters are more easily affected by environment. As against this, **natural classification systems** developed, which were based on natural affinities among the organisms and consider,

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not only the external features, but also internal features, like ultra-structure, anatomy, embryology and phytochemistry. Such a classification for flowering plants was given by George Bentham and Joseph Dalton Hooker.

At present **phylogenetic classification systems** based on evolutionary relationships between the various organisms are acceptable. This assumes that organisms belonging to the same taxa have a common ancestor. We now use information from many other sources too to help resolve difficulties in classification. These become more important when there is no supporting fossil evidence. **Numerical Taxonomy** which is now easily carried out using computers is based on all observable characteristics. Number and codes are assigned to all the characters and the data are then processed. In this way each character is given equal importance and at the same time hundreds of characters can be considered. **Cytotaxonomy,** that is based on cytological information like chromosome number, structure, behaviour and **chemotaxonomy,** that uses the chemical constituents of the plant to resolve confusions, are also used by taxonomists these days.

3.1 ALGAE

Algae are chlorophyll-bearing, simple, thalloid, autotrophic and largely aquatic (both fresh water and marine) organisms. They occur in a variety of other habitats: moist stones, soils and wood. Some of them also occur in association with fungi (lichen) and animals (e.g., on sloth bear).

The form and size of algae is highly variable, ranging from colonial forms like *Volvox* and the filamentous forms like *Ulothrix* and *Spirogyra* (Figure 3.1). A few of the marine forms such as kelps, form massive plant bodies.

The algae reproduce by vegetative, asexual and sexual methods. Vegetative reproduction is by fragmentation. Each fragment develops into a thallus. Asexual reproduction is by the production of different types of spores, the most common being the **zoospores**. They are flagellated (motile) and on germination gives rise to new plants. Sexual reproduction takes place through fusion of two gametes. These gametes can be flagellated and similar in size (as in *Ulothrix*) or non-flagellated (non-motile) but similar in size (as in *Spirogyra*). Such reproduction is called **isogamous**. Fusion of two gametes dissimilar in size, as in species of *Eudorina* is termed as **anisogamous**. Fusion between one large, non-motile (static) female gamete and a smaller, motile male gamete is termed **oogamous**, e.g., *Volvox, Fucus.*

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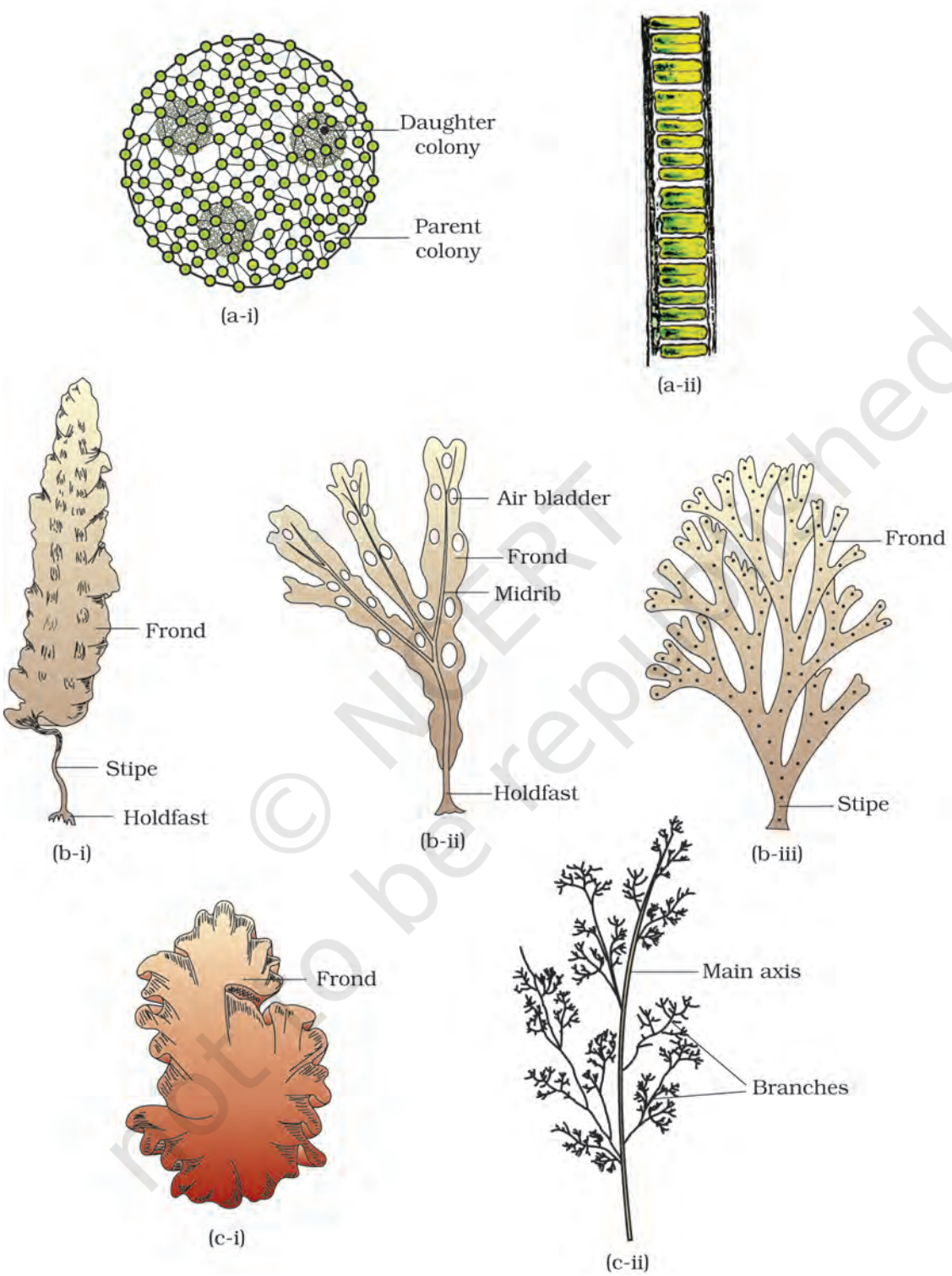

Figure 3.1 Algae : (a) Green algae (i) *Volvox* (ii) *Ulothrix*
(b) Brown algae (i) *Laminaria* (ii) *Fucus* (iii) *Dictyota*
(c) Red algae (i) *Porphyra* (ii) *Polysiphonia*

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Algae are useful to man in a variety of ways. At least a half of the total carbon dioxide fixation on earth is carried out by algae through photosynthesis. Being photosynthetic, they increase the level of dissolved oxygen in their immediate environment. They are of paramount importance as primary producers of energy-rich compounds which form the basis of the food cycles of all aquatic animals. Many species of *Porphyra, Laminaria* and *Sargassum* are among the 70 species of marine algae used as food. Certain marine brown and red algae produce large amounts of hydrocolloids (water holding substances), e.g., **algin** (brown algae) and **carrageen** (red algae) which are used commercially. Agar, one of the commercial products obtained from *Gelidium* and *Gracilaria* are used to grow microbes and in preparations of ice-creams and jellies. *Chlorella,* a unicellular alga rich in proteins, is used as food supplement even by space travellers. The algae are divided into three main classes: **Chlorophyceae, Phaeophyceae** and **Rhodophyceae**.

3.1.1 Chlorophyceae

The members of chlorophyceae are commonly called **green algae**. The plant body may be unicellular, colonial or filamentous. They are usually grass green due to the dominance of pigments chlorophyll *a* and *b*. The pigments are localised in definite chloroplasts. The chloroplasts may be discoid, plate-like, reticulate, cup-shaped, spiral or ribbon-shaped in different species. Most of the members have one or more storage bodies called pyrenoids located in the chloroplasts. Pyrenoids contain protein besides starch. Some algae may store food in the form of oil droplets. Green algae usually have a rigid cell wall made of an inner layer of cellulose and an outer layer of pectose.

Vegetative reproduction usually takes place by fragmentation. Asexual reproduction is by flagellated zoospores produced in zoosporangia. The sexual reproduction shows considerable variation in the type and formation of sex cells and it may be isogamous, anisogamous or oogamous. Some commonly found green algae are: *Chlamydomonas, Volvox, Ulothrix, Spirogyra* and *Chara* (Figure 3.1a).

3.1.2 Phaeophyceae

The members of phaeophyceae or **brown algae** are found primarily in marine habitats. They show great variation in size and form. They range from simple branched, filamentous forms (*Ectocarpus*) to profusely branched forms as represented by kelps, which may reach a height of 100 metres. They possess chlorophyll *a*, *c*, carotenoids and xanthophylls. They vary in colour from olive green to various shades of brown depending upon the amount of the xanthophyll pigment, fucoxanthin present in

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them. Food is stored as complex carbohydrates, which may be in the form of laminarin or mannitol. The vegetative cells have a cellulosic wall usually covered on the outside by a gelatinous coating of **algin**. The protoplast contains, in addition to plastids, a centrally located vacuole and nucleus. The plant body is usually attached to the substratum by a **holdfast**, and has a stalk, the **stipe** and leaf like photosynthetic organ – the **frond**. Vegetative reproduction takes place by fragmentation. Asexual reproduction in most brown algae is by biflagellate zoospores that are pear-shaped and have two unequal laterally attached flagella.

Sexual reproduction may be isogamous, anisogamous or oogamous. Union of gametes may take place in water or within the oogonium (oogamous species). The gametes are pyriform (pear-shaped) and bear two laterally attached flagella. The common forms are *Ectocarpus, Dictyota, Laminaria, Sargassum* and *Fucus* (Figure 3.1b).

3.1.3 Rhodophyceae

The members of rhodophyceae are commonly called **red algae** because of the predominance of the red pigment, r-phycoerythrin in their body. Majority of the red algae are marine with greater concentrations found in the warmer areas. They occur in both well-lighted regions close to the surface of water and also at great depths in oceans where relatively little light penetrates.

The red thalli of most of the red algae are multicellular. Some of them have complex body organisation. The food is stored as floridean starch which is very similar to amylopectin and glycogen in structure.

The red algae usually reproduce vegetatively by fragmentation. They reproduce asexually by non-motile spores and sexually by non-motile

TABLE 3.1 Divisions of Algae and their Main Characteristics

Classes	Common Name	Major Pigments	Stored Food	Cell Wall	Flagellar Number and Position of Insertions	Habitat
Chlorophyceae	Green algae	Chlorophyll *a, b*	Starch	Cellulose	2-8, equal, apical	Fresh water, brackish water, salt water
Phaeophyceae	Brown algae	Chlorophyll *a, c,* fucoxanthin	Mannitol, laminarin	Cellulose and algin	2, unequal, lateral	Fresh water (rare), brackish water, salt water
Rhodophyceae	Red algae	Chlorophyll *a, d,* phycoerythrin	Floridean starch	Cellulose, pectin and poly sulphate esters	Absent	Fresh water (some), brackish water, salt water (most)

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gametes. Sexual reproduction is oogamous and accompanied by complex post fertilisation developments. The common members are: *Polysiphonia*, *Porphyra* (Figure 3.1c), *Gracilaria* and *Gelidium*.

3.2 BRYOPHYTES

Bryophytes include the various mosses and liverworts that are found commonly growing in moist shaded areas in the hills (Figure 3.2).

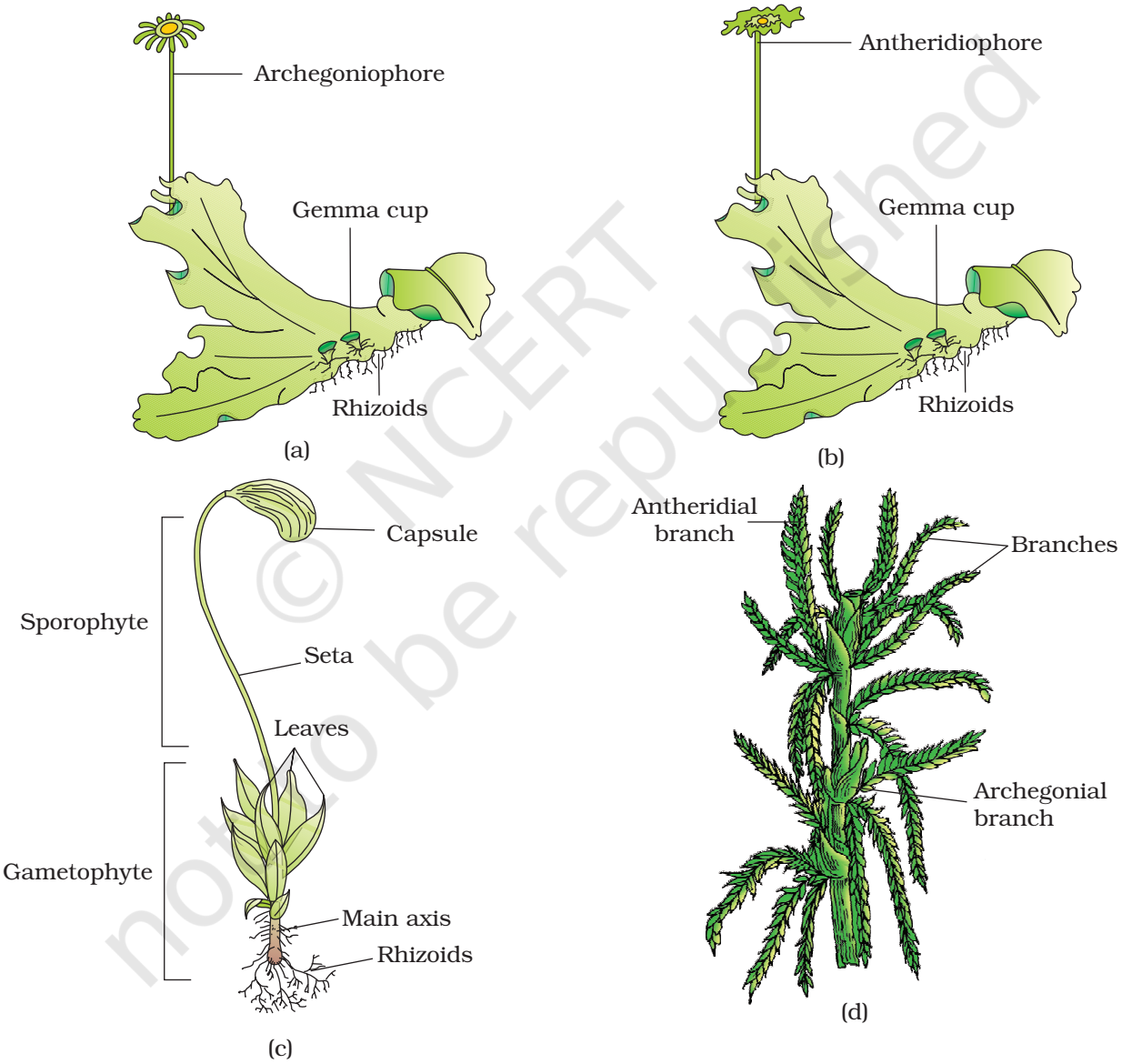

Figure 3.2 Bryophytes: A liverwort – *Marchantia* (a) Female thallus (b) Male thallus Mosses – (c) *Funaria*, gametophyte and sporophyte (d) *Sphagnum* gametophyte

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Bryophytes are also called amphibians of the plant kingdom because these plants can live in soil but are dependent on water for sexual reproduction. They usually occur in damp, humid and shaded localities. They play an important role in plant succession on bare rocks/soil.

The plant body of bryophytes is more differentiated than that of algae. It is thallus-like and prostrate or erect, and attached to the substratum by unicellular or multicellular rhizoids. They lack true roots, stem or leaves. They may possess root-like, leaf-like or stem-like structures. The main plant body of the bryophyte is haploid. It produces gametes, hence is called a **gametophyte**. The sex organs in bryophytes are multicellular. The male sex organ is called **antheridium.** They produce biflagellate **antherozoids**. The female sex organ called **archegonium** is flask-shaped and produces a single egg. The antherozoids are released into water where they come in contact with archegonium. An antherozoid fuses with the egg to produce the zygote. Zygotes do not undergo reduction division immediately. They produce a multicellular body called a **sporophyte**. The sporophyte is not free-living but attached to the photosynthetic gametophyte and derives nourishment from it. Some cells of the sporophyte undergo reduction division (meiosis) to produce haploid spores. These spores germinate to produce gametophyte.

Bryophytes in general are of little economic importance but some mosses provide food for herbaceous mammals, birds and other animals. Species of *Sphagnum*, a moss, provide peat that have long been used as fuel, and as packing material for trans-shipment of living material because of their capacity to hold water. Mosses along with lichens are the first organisms to colonise rocks and hence, are of great ecological importance. They decompose rocks making the substrate suitable for the growth of higher plants. Since mosses form dense mats on the soil, they reduce the impact of falling rain and prevent soil erosion. The bryophytes are divided into **liverworts** and **mosses**.

3.2.1 Liverworts

The liverworts grow usually in moist, shady habitats such as banks of streams, marshy ground, damp soil, bark of trees and deep in the woods. The plant body of a liverwort is thalloid, e.g., *Marchantia*. The thallus is dorsiventral and closely appressed to the substrate. The leafy members have tiny leaf-like appendages in two rows on the stem-like structures.

Asexual reproduction in liverworts takes place by fragmentation of thalli, or by the formation of specialised structures called **gemmae** (sing. gemma). Gemmae are green, multicellular, asexual buds, which develop in small receptacles called gemma cups located on the thalli. The gemmae become detached from the parent body and germinate to form new individuals. During sexual reproduction, male and female sex

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organs are produced either on the same or on different thalli. The sporophyte is differentiated into a foot, seta and capsule. After meiosis, spores are produced within the capsule. These spores germinate to form free-living gametophytes.

3.2.2 Mosses

The predominant stage of the life cycle of a moss is the gametophyte which consists of two stages. The first stage is the **protonema** stage, which develops directly from a spore. It is a creeping, green, branched and frequently filamentous stage. The second stage is the **leafy stage**, which develops from the secondary protonema as a lateral bud. They consist of upright, slender axes bearing spirally arranged leaves. They are attached to the soil through multicellular and branched rhizoids. This stage bears the sex organs.

Vegetative reproduction in mosses is by fragmentation and budding in the secondary protonema. In sexual reproduction, the sex organs antheridia and archegonia are produced at the apex of the leafy shoots. After fertilisation, the zygote develops into a sporophyte, consisting of a foot, seta and capsule. The sporophyte in mosses is more elaborate than that in liverworts. The capsule contains spores. Spores are formed after meiosis. The mosses have an elaborate mechanism of spore dispersal. Common examples of mosses are *Funaria, Polytrichum* and *Sphagnum* (Figure 3.2).

3.3 Pteridophytes

The Pteridophytes include horsetails and ferns. Pteridophytes are used for medicinal purposes and as soil-binders. They are also frequently grown as ornamentals. Evolutionarily, they are the first terrestrial plants to possess vascular tissues – xylem and phloem. You shall study more about these tissues in Chapter 6. The pteridophytes are found in cool, damp, shady places though some may flourish well in sandy-soil conditions.

You may recall that in bryophytes the dominant phase in the life cycle is the gametophytic plant body. However, in pteridophytes, the main plant body is a sporophyte which is differentiated into true root, stem and leaves (Figure 3.3). These organs possess well-differentiated vascular tissues. The leaves in pteridophyta are small (microphylls) as in *Selaginella* or large (macrophylls) as in ferns. The sporophytes bear sporangia that are subtended by leaf-like appendages called **sporophylls**. In some cases sporophylls may form distinct compact structures called strobili or cones (*Selaginella, Equisetum*). The sporangia produce spores by meiosis in spore mother cells. The spores germinate to give rise to inconspicuous, small but multicellular,

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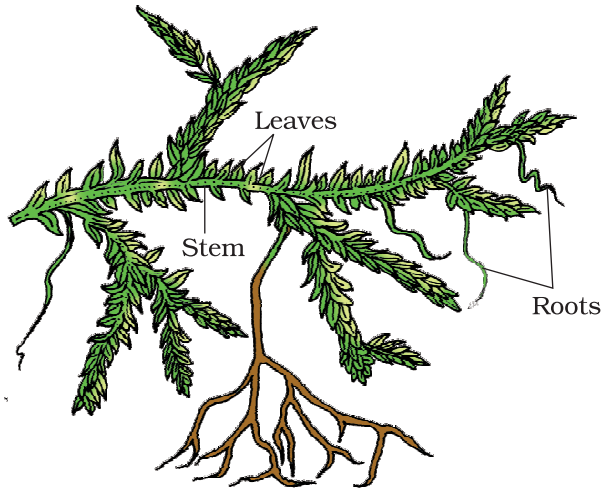
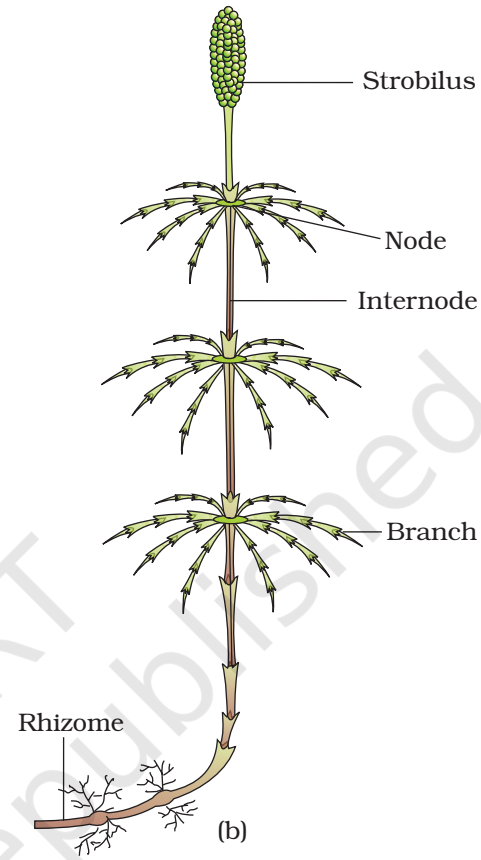


(a)



(b)

(c)

(d)

Figure 3.3 Pteridophytes : (a) *Selaginella* (b) *Equisetum* (c) Fern (d) *Salvinia*

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free-living, mostly photosynthetic thalloid gametophytes called **prothallus**. These gametophytes require cool, damp, shady places to grow. Because of this specific restricted requirement and the need for water for fertilisation, the spread of living pteridophytes is limited and restricted to narrow geographical regions. The gametophytes bear male and female sex organs called antheridia and archegonia, respectively. Water is required for transfer of antherozoids – the male gametes released from the antheridia, to the mouth of archegonium. Fusion of male gamete with the egg present in the archegonium result in the formation of zygote. Zygote thereafter produces a multicellular well-differentiated sporophyte which is the dominant phase of the pteridophytes. In majority of the pteridophytes all the spores are of similar kinds; such plants are called **homosporous**. Genera like *Selaginella* and *Salvinia* which produce two kinds of spores, macro (large) and micro (small) spores, are known as **heterosporous**. The megaspores and microspores germinate and give rise to female and male gametophytes, respectively. The female gametophytes in these plants are retained on the parent sporophytes for variable periods. The development of the zygotes into young embryos take place within the female gametophytes. This event is a precursor to the **seed habit** considered an important step in evolution.

The pteridophytes are further classified into four classes: Psilopsida *(Psilotum);* Lycopsida *(Selaginella, Lycopodium)*, Sphenopsida *(Equisetum)* and Pteropsida *(Dryopteris, Pteris, Adiantum)*.

3.4 GYMNOSPERMS

The gymnosperms (*gymnos* : naked, *sperma* : seeds) are plants in which the ovules are not enclosed by any ovary wall and remain exposed, both before and after fertilisation. The seeds that develop post-fertilisation, are not covered, i.e., are naked. Gymnosperms include medium-sized trees or tall trees and shrubs (Figure 3.4). One of the gymnosperms, the giant redwood tree *Sequoia* is one of the tallest tree species. The roots are generally tap roots. Roots in some genera have fungal association in the form of **mycorrhiza** *(Pinus)*, while in some others *(Cycas)* small specialised roots called coralloid roots are associated with N_2- fixing cyanobacteria. The stems are unbranched (*Cycas*) or branched (*Pinus, Cedrus*). The leaves may be simple or compound. In *Cycas* the pinnate leaves persist for a few years. The leaves in gymnosperms are well-adapted to withstand extremes of temperature, humidity and wind. In conifers, the needle-like leaves reduce the surface area. Their thick cuticle and sunken stomata also help to reduce water loss.

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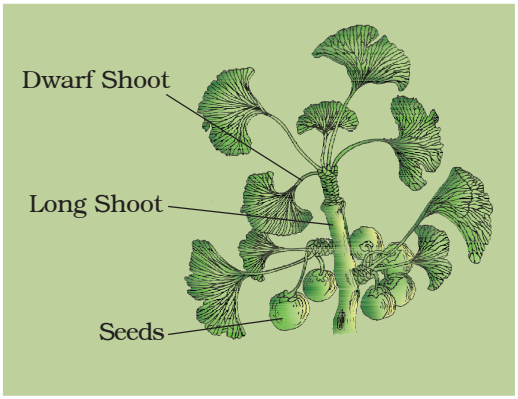
The gymnosperms are heterosporous; they produce haploid microspores and megaspores. The two kinds of spores are produced within sporangia that are borne on sporophylls which are arranged spirally along an axis to form lax or compact strobili or **cones**. The strobili bearing **microsporophylls** and **microsporangia** are called microsporangiate or **male strobili**. The microspores develop into a male gametophytic generation which is highly reduced and is confined to only a limited number of cells. This reduced gametophyte is called a **pollen grain**. The development of pollen grains take place within the microsporangia. The cones bearing megasporophylls with ovules or **megasporangia** are called macrosporangiate or **female strobili**. The male or female cones or strobili may be borne on the same tree (*Pinus*). However, in *cycas* male cones and megasporophylls are borne on different trees. The megaspore mother cell is differentiated from one of the cells of the nucellus. The nucellus is protected by envelopes and the composite structure is called an **ovule**. The ovules are borne on megasporophylls which may be clustered to form the female cones. The megaspore mother cell divides meiotically to form four megaspores. One of the megaspores enclosed within the **megasporangium** develops into a multicellular female gametophyte that bears two or more **archegonia** or female sex organs. The multicellular female gametophyte is also retained within megasporangium.

Unlike bryophytes and pteridophytes, in gymnosperms, the male and the female gametophytes do not have an independent free-living existence. They remain within the sporangia retained on the sporophytes. The pollen grain is released from the microsporangium. They are carried in air currents and come in contact with the opening of the ovules borne on megasporophylls. The pollen tube carrying the male gametes grows towards archegonia in the ovules and discharge their contents near the mouth of the archegonia. Following fertilisation, zygote develops into an embryo and the ovules into seeds. These seeds are not covered.

(a)

(b)



(c)

Figure 3.4 Gymnosperms: (a) *Cycas* (b) *Pinus* (c) *Ginkgo*

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3.5 ANGIOSPERMS

Unlike the gymnosperms where the ovules are naked, in the angiosperms or flowering plants, the pollen grains and ovules are developed in specialised structures called **flowers**. In angiosperms, the seeds are enclosed in fruits. The angiosperms are an exceptionally large group of plants occurring in wide range of habitats. They range in size from the smallest *Wolffia* to tall trees of *Eucalyptus* (over 100 metres). They provide us with food, fodder, fuel, medicines and several other commercially important products. They are divided into two classes : the **dicotyledons** and the **monocotyledons** (Figure 3.5).

(a) (b)

Figure 3.5 Angiosperms : (a) A dicotyledon (b) A monocotyledon

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SUMMARY

Plant kingdom includes algae, bryophytes, pteridophytes, gymnosperms and angiosperms. Algae are chlorophyll-bearing simple, thalloid, autotrophic and largely aquatic organisms. Depending on the type of pigment possesed and the type of stored food, algae are classfied into three classes, namely Chlorophyceae, Phaeophyceae and Rhodophyceae. Algae usually reproduce vegetatively by fragmentation, asexually by formation of different types of spores and sexually by formation of gametes which may show isogamy, anisogamy or oogamy.

Bryophytes are plants which can live in soil but are dependent on water for sexual reproduction. Their plant body is more differentiated than that of algae. It is thallus-like and prostrate or erect and attached to the substratum by rhizoids. They possess root-like, leaf-like and stem-

like structures. The bryophytes are divided into liverworts and mosses. The plant body of liverworts is thalloid and dorsiventral whereas mosses have upright, slender axes bearing spirally arranged leaves. The main plant body of a bryophyte is gamete-producing and is called a gametophyte. It bears the male sex organs called antheridia and female sex organs called archegonia. The male and female gametes produced fuse to form zygote which produces a multicellular body called a sporophyte. It produces haploid spores. The spores germinate to form gametophytes.

In pteridophytes the main plant is a sporophyte which is differentiated into true root, stem and leaves. These organs possess well-differentiated vascular tissues. The sporophytes bear sporangia which produce spores. The spores germinate to form gametophytes which require cool, damp places to grow. The gametophytes bear male and female sex organs called antheridia and archegonia, respectively. Water is required for transfer of male gametes to archegonium where zygote is formed after fertilisation. The zygote produces a sporophyte.

The gymnosperms are the plants in which ovules are not enclosed by any ovary wall. After fertilisation the seeds remain exposed and therefore these plants are called naked-seeded plants. The gymnosperms produce microspores and megaspores which are produced in microsporangia and megasporangia borne on the sporophylls. The sporophylls – microsporophylls and megasporophylls – are arranged spirally on axis to form male and female cones, respectively. The pollen grain germinates and pollen tube releases the male gamete into the ovule, where it fuses with the egg cell in archegonia. Following fertilisation, the zygote develops into embryo and the ovules into seeds.

The angiosperms are divided into two classes – the dicotyledons and the monocotyledons.

EXERCISES

1. What is the basis of classification of algae?
2. When and where does reduction division take place in the life cycle of a liverwort, a moss, a fern, a gymnosperm and an angiosperm?
3. Name three groups of plants that bear archegonia. Briefly describe the life cycle of any one of them.
4. Mention the ploidy of the following: protonemal cell of a moss; primary endosperm nucleus in dicot, leaf cell of a moss; prothallus cell of a ferm; gemma cell in *Marchantia*; meristem cell of monocot, ovum of a liverwort, and zygote of a fern.

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5. Write a note on economic importance of algae and gymnosperms.
6. Both gymnosperms and angiosperms bear seeds, then why are they classified separately?
7. What is heterospory? Briefly comment on its significance. Give two examples.
8. Explain briefly the following terms with suitable examples:-
   (i) protonema
   (ii) antheridium
   (iii) archegonium
   (iv) diplontic
   (v) sporophyll
   (vi) isogamy
9. Differentiate between the following:-
   (i) red algae and brown algae
   (ii) liverworts and moss
   (iii) homosporous and heterosporous pteridophyte
10. Match the following (column I with column II)

Column I	**Column II**
(a) *Chlamydomonas*	(i) Moss
(b) *Cycas*	(ii) Pteridophyte
(c) *Selaginella*	(iii) Algae
(d) *Sphagnum*	(iv) Gymnosperm

11. Describe the important characteristics of gymnosperms.

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Chapter 4
Animal Kingdom

4.1 *Basis of Classification*
4.2 *Classification of Animals*

When you look around, you will observe different animals with different structures and forms. As over a million species of animals have been described till now, the need for classification becomes all the more important. The classification also helps in assigning a systematic position to newly described species.

4.1 Basis of Classification

Inspite of differences in structure and form of different animals, there are fundamental features common to various individuals in relation to the arrangement of cells, body symmetry, nature of coelom, patterns of digestive, circulatory or reproductive systems. These features are used as the basis of animal classification and some of them are discussed here.

4.1.1 Levels of Organisation

Though all members of Animalia are multicellular, all of them do not exhibit the same pattern of organisation of cells. For example, in sponges, the cells are arranged as loose cell aggregates, i.e., they exhibit **cellular level** of organisation. Some division of labour (activities) occur among the cells. In coelenterates, the arrangement of cells is more complex. Here the cells performing the same function are arranged into tissues, hence is called **tissue level** of organisation. A still higher level of organisation, i.e., **organ level** is exhibited by members of Platyhelminthes and other higher phyla where tissues are grouped together to form organs, each specialised for a particular function. In animals like Annelids, Arthropods, Molluscs,

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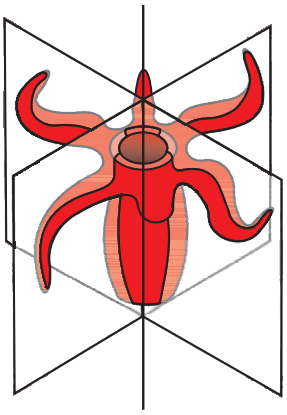

Figure 4.1 (a) Radial symmetry

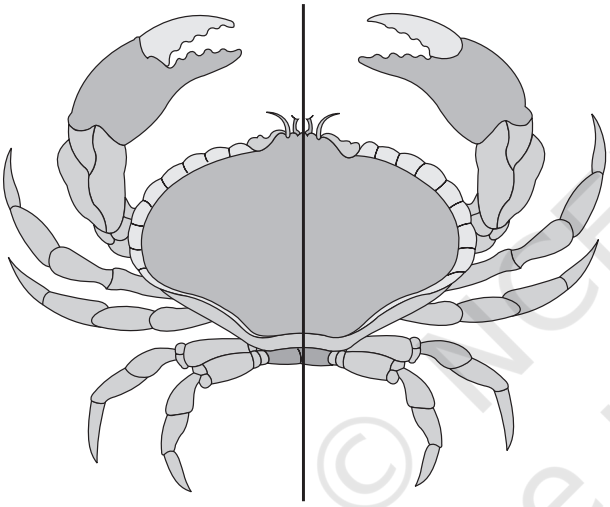

Figure 4.1 (b) Bilateral symmetry

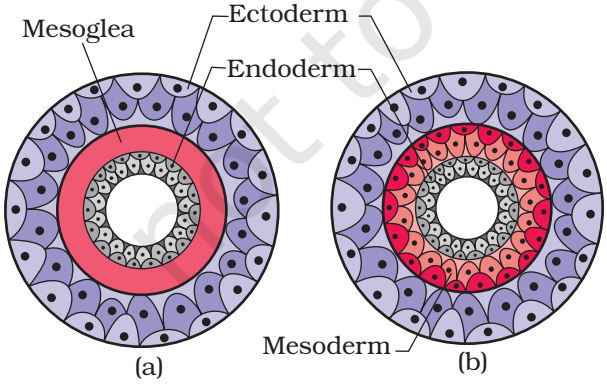

Figure 4.2 Showing germinal layers : (a) Diploblastic (b) Triploblastic

Echinoderms and Chordates, organs have associated to form functional systems, each system concerned with a specific physiological function. This pattern is called **organ system** level of organisation. Organ systems in different groups of animals exhibit various patterns of complexities. For example, the digestive system in Platyhelminthes has only a single opening to the outside of the body that serves as both mouth and anus, and is hence called incomplete. A complete digestive system has two openings, mouth and anus. Similarly, the circulatory system may be of two types:

(i) **open type** in which the blood is pumped out of the heart and the cells and tissues are directly bathed in it and

(ii) **closed type** in which the blood is circulated through a series of vessels of varying diameters (arteries, veins and capillaries).

4.1.2 Symmetry

Animals can be categorised on the basis of their symmetry. Sponges are mostly **asymmetrical,** i.e., any plane that passes through the centre does not divide them into equal halves. When any plane passing through the central axis of the body divides the organism into two identical halves, it is called **radial symmetry**. Coelenterates, ctenophores and echinoderms have this kind of body plan (Figure 4.1a). Animals like annelids, arthropods, etc., where the body can be divided into identical left and right halves in only one plane, exhibit **bilateral symmetry** (Figure 4.1b).

4.1.3 Diploblastic and Triploblastic Organisation

Animals in which the cells are arranged in two embryonic layers, an external **ectoderm** and an internal **endoderm**, are called **diploblastic** animals, e.g., coelenterates. An undifferentiated layer, mesoglea, is present in between the ectoderm and the endoderm (Figure 4.2a).

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Those animals in which the developing embryo has a third germinal layer, **mesoderm**, in between the ectoderm and endoderm, are called **triploblastic** animals (platyhelminthes to chordates, Figure 4.2b).

4.1.4 Coelom

Presence or absence of a cavity between the body wall and the gut wall is very important in classification. The body cavity, which is lined by mesoderm is called **coelom**. Animals possessing coelom are called **coelomates,** e.g., annelids, molluscs, arthropods, echinoderms, hemichordates and chordates (Figure 4.3a). In some animals, the body cavity is not lined by mesoderm, instead, the mesoderm is present as scattered pouches in between the ectoderm and endoderm. Such a body cavity is called pseudocoelom and the animals possessing them are called **pseudocoelomates,** e.g., aschelminthes (Figure 4.3b). The animals in which the body cavity is absent are called **acoelomates,** e.g., platyhelminthes (Figure 4.3c).

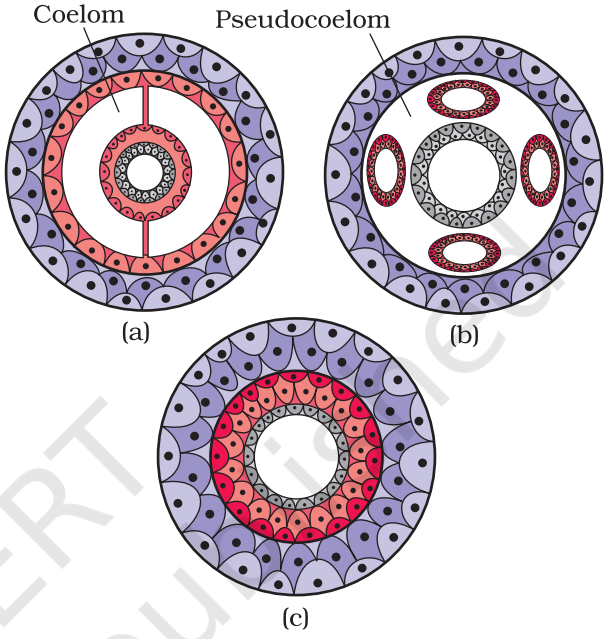

Figure 4.3 Diagrammatic sectional view of : (a) Coelomate (b) Pseudocoelomate (c) Acoelomate

4.1.5 Segmentation

In some animals, the body is externally and internally divided into segments with a serial repetition of at least some organs. For example, in earthworm, the body shows this pattern called metameric segmentation and the phenomenon is known as **metamerism**.

4.1.6 Notochord

Notochord is a mesodermally derived rod-like structure formed on the dorsal side during embryonic development in some animals. Animals with notochord are called chordates and those animals which do not form this structure are called non-chordates, e.g., porifera to echinoderms.

4.2 CLASSIFICATION OF ANIMALS

The broad classification of Animalia, based on common fundamental features as mentioned in the preceding sections, is given in Figure 4.4.

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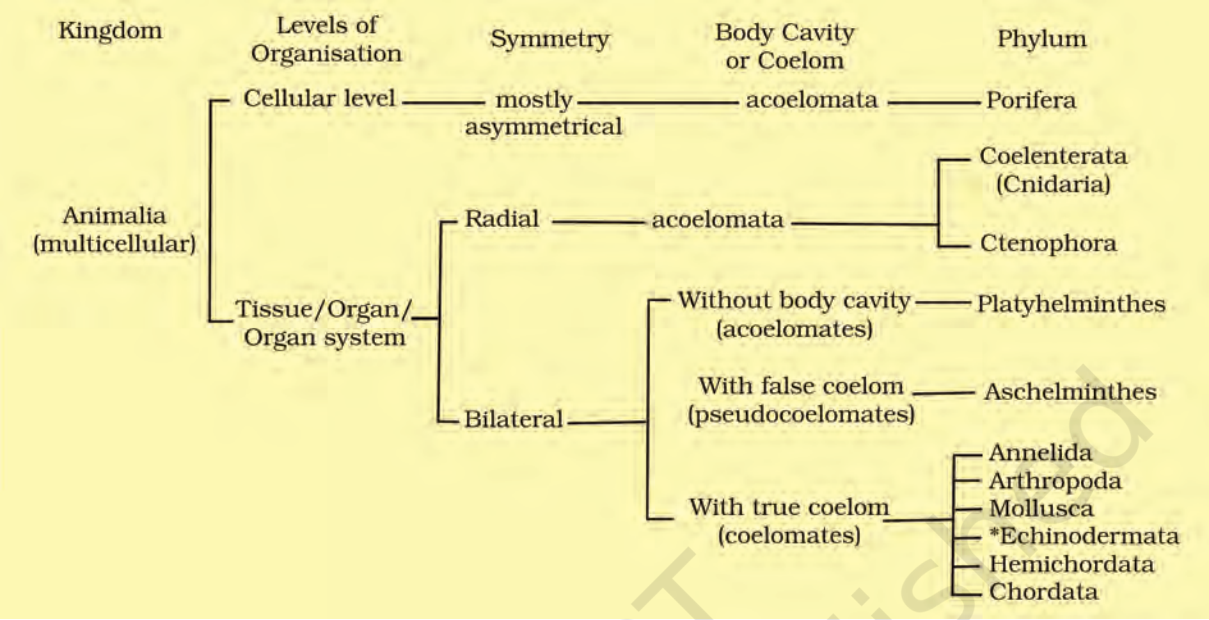

*Echinodermata exhibits radial or bilateral symmetry depending on the stage.

Figure 4.4 Broad classification of Kingdom Animalia based on common fundamental features

The important characteristic features of the different phyla are described.

4.2.1 Phylum – Porifera

Members of this phylum are commonly known as sponges. They are generally marine and mostly asymmetrical animals (Figure 4.5). These are primitive multicellular animals and have cellular level of organisation. Sponges have a water transport or canal system. Water enters through minute pores (**ostia**) in the body wall into a central cavity, **spongocoel**, from where it goes out through the **osculum**. This pathway of water transport is helpful in food gathering, respiratory exchange and removal of waste. **Choanocytes** or collar cells line the spongocoel and the canals. Digestion is intracellular. The body is supported by a skeleton made up of **spicules** or **spongin fibres**. Sexes are not separate (**hermaphrodite**), i.e., eggs and sperms are produced by the same individual. Sponges reproduce asexually by fragmentation and sexually by formation of gametes. Fertilisation is internal and development is indirect having a larval stage which is morphologically distinct from the adult.

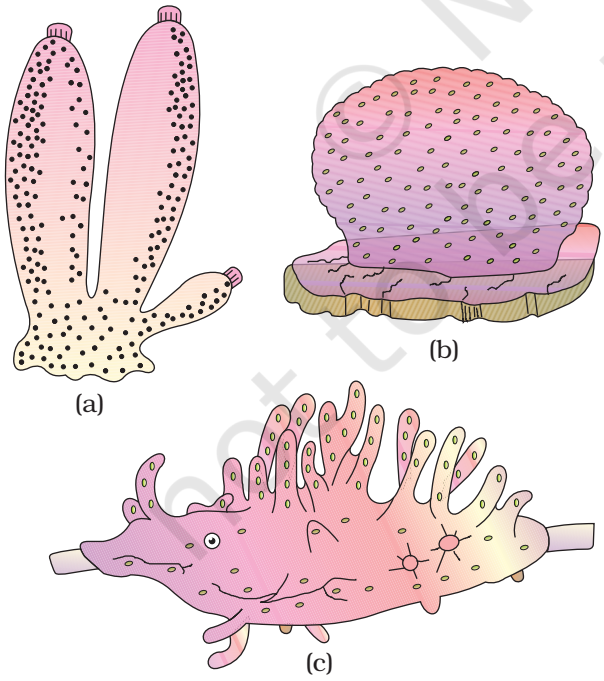

Figure 4.5 Examples of Porifera : (a) *Sycon* (b) *Euspongia* (c) *Spongilla*

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Examples: *Sycon* (Scypha), *Spongilla* (Fresh water sponge) and *Euspongia* (Bath sponge).

4.2.2 Phylum – Coelenterata (Cnidaria)

They are aquatic, mostly marine, sessile or free-swimming, radially symmetrical animals (Figure 4.6). The name cnidaria is derived from the

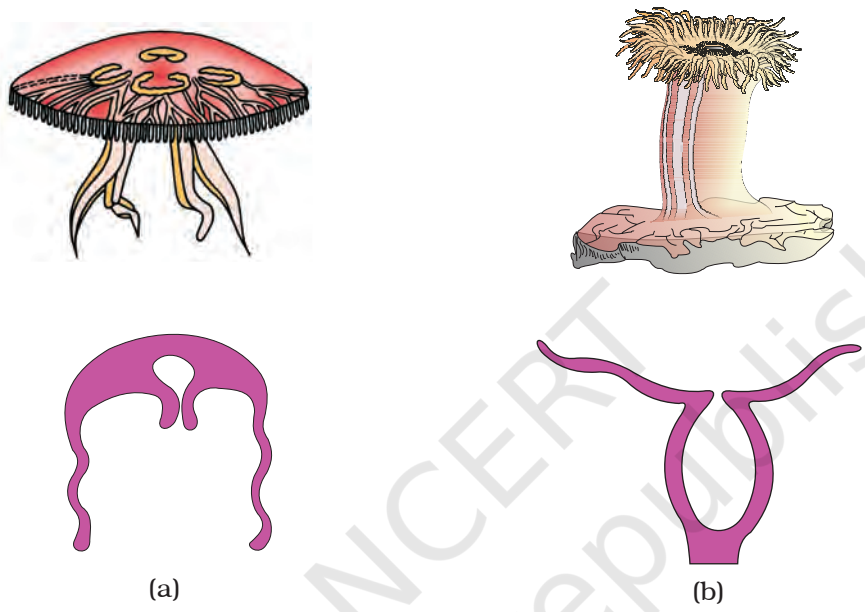

Figure 4.6 Examples of Coelenterata indicating outline of their body form : (a) *Aurelia* (Medusa) (b) *Adamsia* (Polyp)

cnidoblasts or cnidocytes (which contain the stinging capsules or nematocysts) present on the tentacles and the body. Cnidoblasts are used for anchorage, defense and for the capture of prey (Figure 4.7). Cnidarians exhibit tissue level of organisation and are diploblastic. They have a central gastro-vascular cavity with a single opening, mouth on **hypostome**. Digestion is extracellular and intracellular. Some of the cnidarians, e.g., **corals** have a skeleton composed of calcium carbonate. Cnidarians exhibit two basic body forms called **polyp** and **medusa** (Figure 4.6). The former is a sessile and cylindrical form like Hydra, *Adamsia*, etc. whereas, the latter is umbrella-shaped and free-swimming like *Aurelia* or jelly fish. Those cnidarians which exist in both forms exhibit alternation of generations (Metagenesis), i.e., polyps produce medusae asexually and medusae form the polyps sexually (e.g., *Obelia*).

Figure 4.7 Diagrammatic view of Cnidoblast

Examples: *Physalia* (Portuguese man-of-war), *Adamsia* (Sea anemone), *Pennatula* (Sea-pen), *Gorgonia* (Sea-fan) and *Meandrina* (Brain coral).

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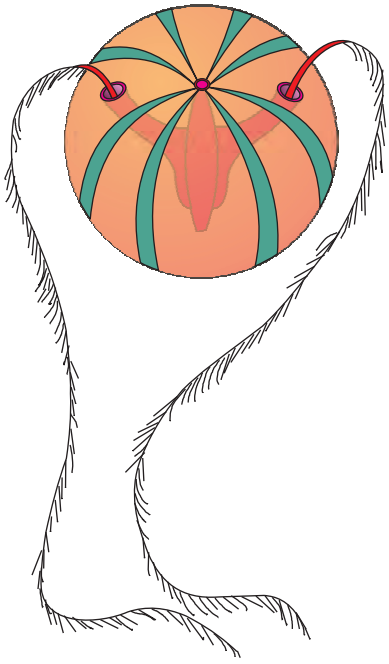


Figure 4.8 Example of Ctenophora (*Pleurobrachia*)

4.2.3 Phylum – Ctenophora

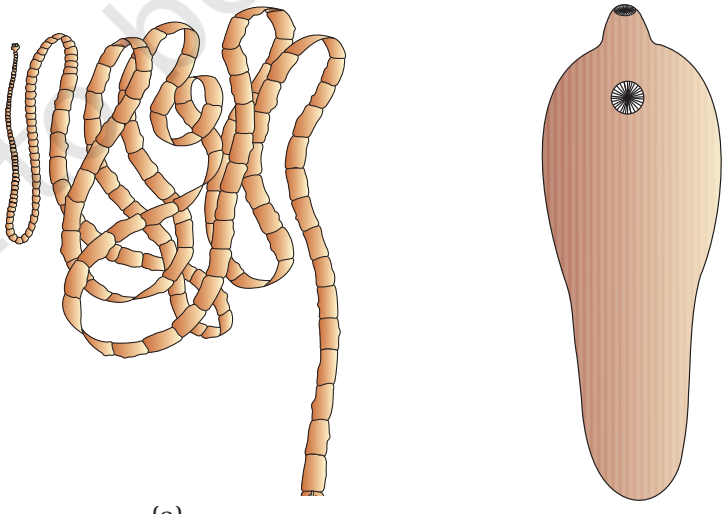
Ctenophores, commonly known as **sea walnuts** or **comb jellies** are exclusively marine, radially symmetrical, diploblastic organisms with tissue level of organisation. The body bears eight external rows of ciliated **comb plates**, which help in locomotion (Figure 4.8). Digestion is both extracellular and intracellular. **Bioluminescence** (the property of a living organism to emit light) is well-marked in ctenophores. Sexes are not separate. Reproduction takes place only by sexual means. Fertilisation is external with indirect development.

Examples: *Pleurobrachia* and *Ctenoplana*.

4.2.4 Phylum – Platyhelminthes

They have dorso-ventrally flattened body, hence are called **flatworms** (Figure 4.9). These are mostly endoparasites found in animals including human beings. Flatworms are bilaterally symmetrical, triploblastic and acoelomate animals with organ level of organisation. Hooks and suckers are present in the parasitic forms. Some of them absorb nutrients from the host directly through their body surface. Specialised cells called flame cells help in osmoregulation and excretion. Sexes are not separate. Fertilisation is internal and development is through many larval stages. Some members like *Planaria* possess high regeneration capacity.

Examples: *Taenia* (Tapeworm), *Fasciola* (Liver fluke).



(a) (b)

Figure 4.9 Examples of Platyhelminthes : (a) Tape worm (b) Liver fluke

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4.2.5 Phylum – Aschelminthes

The body of the aschelminthes is circular in cross-section, hence, the name **roundworms** (Figure 4.10). They may be freeliving, aquatic and terrestrial or parasitic in plants and animals. Roundworms have organ-system level of body organisation. They are bilaterally symmetrical, triploblastic and pseudocoelomate animals. Alimentary canal is complete with a well-developed **muscular pharynx.** An excretory tube removes body wastes from the body cavity through the excretory pore. Sexes are separate (**dioecious**), i.e., males and females are distinct. Often females are longer than males. Fertilisation is internal and development may be direct (the young ones resemble the adult) or indirect.

Examples : *Ascaris* (Roundworm), *Wuchereria* (Filaria worm), *Ancylostoma* (Hookworm).

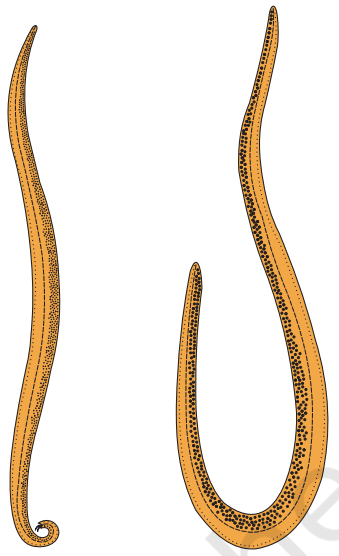

Figure 4.10 Example of Aschelminthes: Roundworm

4.2.6 Phylum – Annelida

They may be aquatic (marine and fresh water) or terrestrial; free-living, and sometimes parasitic. They exhibit organ-system level of body organisation and bilateral symmetry. They are triploblastic, metamerically segmented and coelomate animals. Their body surface is distinctly marked out into **segments** or **metameres** and, hence, the phylum name Annelida (Latin, *annulus* : little ring) (Figure 4.11). They possess longitudinal and circular muscles which help in locomotion. Aquatic annelids like *Nereis* possess lateral appendages, **parapodia**, which help in swimming. A closed circulatory system is present. **Nephridia** (sing. nephridium) help in osmoregulation and excretion. Neural system consists of paired ganglia (sing. ganglion) connected by lateral nerves to a double ventral nerve cord. *Nereis*, an aquatic form, is dioecious, but earthworms and leeches are monoecious. Reproduction is sexual.

Examples : *Nereis*, *Pheretima* (Earthworm) and *Hirudinaria* (Blood sucking leech).

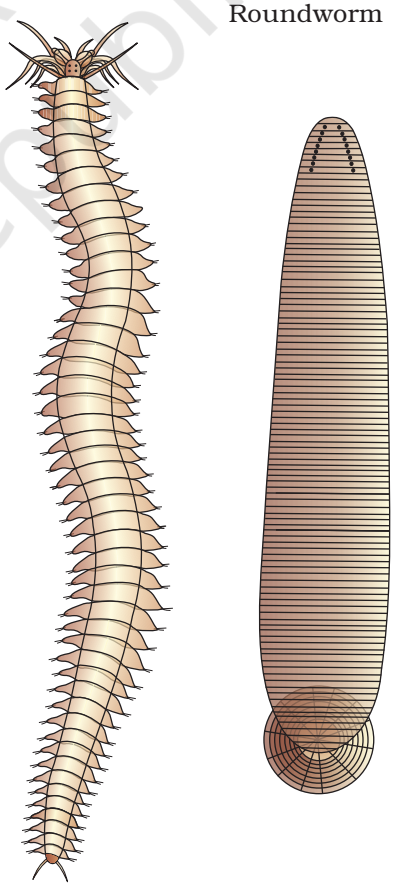

Figure 4.11 Examples of Annelida : (a) *Nereis* (b) *Hirudinaria*

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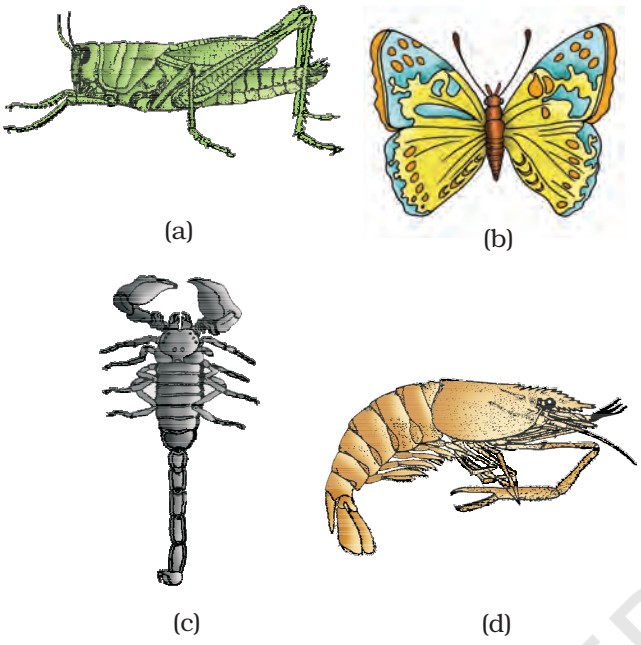

Figure 4.12 Examples of Arthropoda : (a) Locust (b) Butterfly (c) Scorpion (d) Prawn

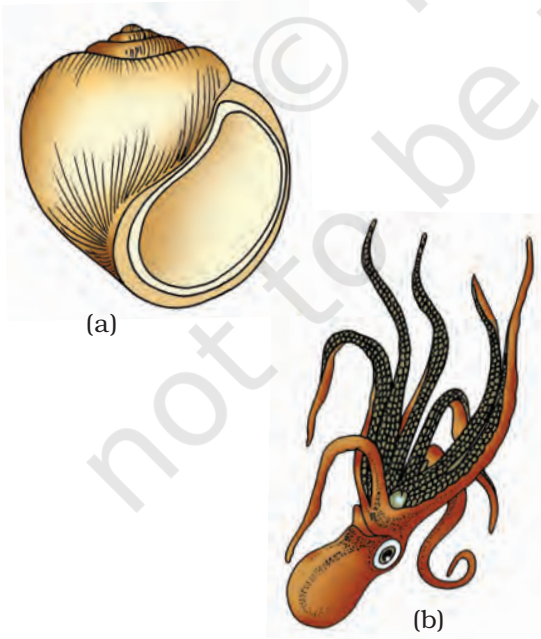

Figure 4.13 Examples of Mollusca : (a) *Pila* (b) *Octopus*

4.2.7 Phylum – Arthropoda

This is the **largest phylum** of Animalia which includes insects. Over two-thirds of all named species on earth are arthropods (Figure 4.12). They have organ-system level of organisation. They are bilaterally symmetrical, triploblastic, segmented and coelomate animals. The body of arthropods is covered by chitinous exoskeleton. The body consists of **head**, **thorax** and **abdomen**. They have **jointed appendages** (arthros-joint, poda-appendages). Respiratory organs are gills, book gills, book lungs or tracheal system. Circulatory system is of open type. Sensory organs like antennae, eyes (compound and simple), statocysts or balancing organs are present. Excretion takes place through **malpighian tubules**. They are mostly dioecious. Fertilisation is usually internal. They are mostly oviparous. Development may be direct or indirect.

Examples: Economically important insects – *Apis* (Honey bee), *Bombyx* (Silkworm), *Laccifer* (Lac insect)

Vectors – *Anopheles, Culex* and *Aedes* (Mosquitoes)

Gregarious pest – *Locusta* (Locust)

Living fossil – *Limulus* (King crab).

4.2.8 Phylum – Mollusca

This is the **second largest** animal phylum (Figure 4.13). Molluscs are terrestrial or aquatic (marine or fresh water) having an organ-system level of organisation. They are bilaterally symmetrical, triploblastic and coelomate animals. Body is covered by a calcareous shell and is unsegmented with a distinct **head**, **muscular foot** and **visceral hump**. A soft and spongy layer of skin forms a mantle over the visceral hump. The space between the hump and the mantle is called the mantle cavity in which feather like gills are present. They have respiratory and excretory functions. The anterior head region has sensory tentacles. The mouth contains a file-like rasping organ for feeding, called **radula**.

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They are usually dioecious and oviparous with indirect development.
Examples: *Pila* (Apple snail), *Pinctada* (Pearl oyster), *Sepia* (Cuttlefish), *Loligo* (Squid), *Octopus* (Devil fish), *Aplysia* (Sea-hare), *Dentalium* (Tusk shell) and *Chaetopleura* (Chiton).

4.2.9 Phylum – Echinodermata

These animals have an endoskeleton of calcareous ossicles and, hence, the name Echinodermata (Spiny bodied, Figure 4.14). All are marine with organ-system level of organisation. The adult echinoderms are radially symmetrical but larvae are bilaterally symmetrical. They are triploblastic and coelomate animals. Digestive system is complete with mouth on the lower (ventral) side and anus on the upper (dorsal) side. The most distinctive feature of echinoderms is the presence of **water vascular system** which helps in locomotion, capture and transport of food and respiration. An excretory system is absent. Sexes are separate. Reproduction is sexual. Fertilisation is usually external. Development is indirect with free-swimming larva.
Examples: *Asterias* (Star fish), *Echinus* (Sea urchin), *Antedon* (Sea lily), *Cucumaria* (Sea cucumber) and *Ophiura* (Brittle star).

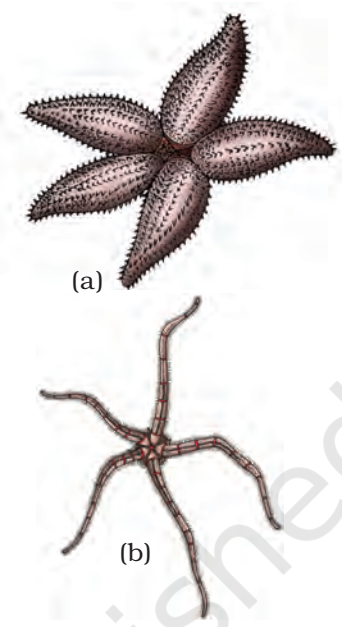

Figure 4.14 Examples of Echinodermata : (a) *Asterias* (b) *Ophiura*

4.2.10 Phylum – Hemichordata

Hemichordata was earlier considered as a sub-phylum under phylum Chordata. But now it is placed as a separate phylum under non-chordata. Hemichordates have a rudimentary structure in the collar region called stomochord, a structure similar to notochord.

This phylum consists of a small group of **worm-like** marine animals with organ-system level of organisation. They are bilaterally symmetrical, triploblastic and coelomate animals. The body is cylindrical and is composed of an anterior **proboscis**, a **collar** and a long **trunk** (Figure 4.15). Circulatory system is of open type. Respiration takes place through gills. Excretory organ is proboscis gland. Sexes are separate. Fertilisation is external. Development is indirect.

Examples: *Balanoglossus* and *Saccoglossus.*

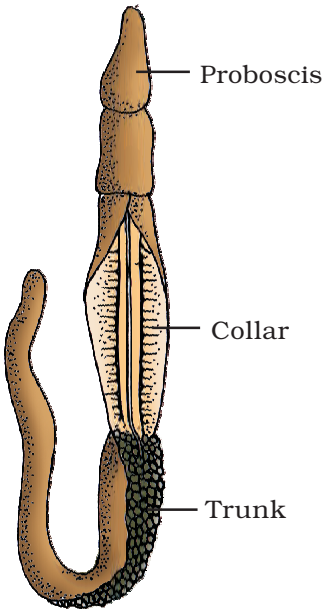

Figure 4.15 *Balanoglossus*

4.2.11 Phylum – Chordata

Animals belonging to phylum Chordata are fundamentally characterised by the presence of a **notochord**, a **dorsal**

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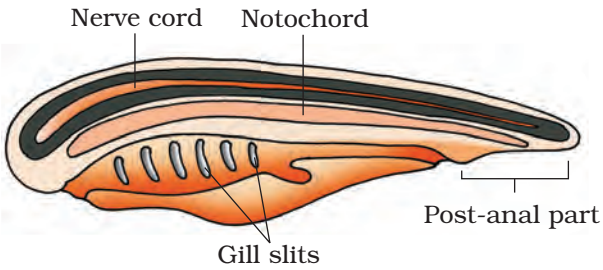

Figure 4.16 Chordata characteristics

hollow nerve cord and **paired pharyngeal gill slits** (Figure 4.16). These are bilaterally symmetrical, triploblastic, coelomate with organ-system level of organisation. They possess a post anal tail and a closed circulatory system.

Table 4.1 presents a comparison of salient features of chordates and non-chordates.

TABLE 4.1 Comparison of Chordates and Non-chordates

S.No.	Chordates	Non-chordates
1.	Notochord present.	Notochord absent.
2.	Central nervous system is dorsal, hollow and single.	Central nervous system is ventral, solid and double.
3.	Pharynx perforated by gill slits.	Gill slits are absent.
4.	Heart is ventral.	Heart is dorsal (if present).
5.	A post-anal part (tail) is present.	Post-anal tail is absent.

Figure 4.17 *Ascidia*

Phylum Chordata is divided into three subphyla: **Urochordata** or **Tunicata**, **Cephalochordata** and **Vertebrata**.

Subphyla Urochordata and Cephalochordata are often referred to as **protochordates** (Figure 4.17) and are exclusively marine. In Urochordata, notochord is present only in larval tail, while in Cephalochordata, it extends from head to tail region and is persistent throughout their life.

Examples: Urochordata – *Ascidia, Salpa, Doliolum;* Cephalochordata – *Branchiostoma* (Amphioxus or Lancelet).

The members of subphylum Vertebrata possess notochord during the embryonic period. The notochord is replaced by a cartilaginous or bony **vertebral column** in the adult. Thus all vertebrates are chordates but all chordates are not vertebrates. Besides the basic chordate characters, vertebrates have a ventral muscular heart with two, three or four chambers, kidneys for excretion and osmoregulation and paired appendages which may be fins or limbs.

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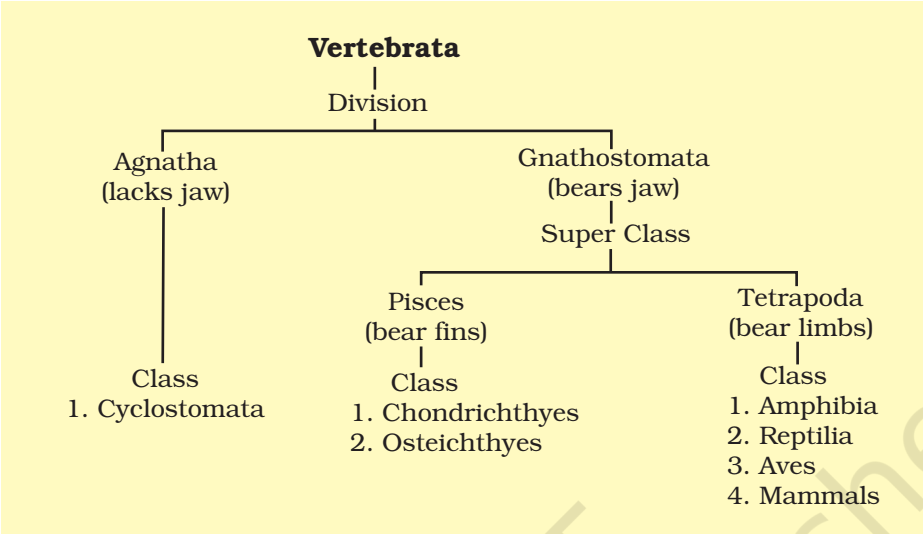
The subphylum Vertebrata is further divided as follows:



4.2.11.1 Class – Cyclostomata

All living members of the class Cyclostomata are ectoparasites on some fishes. They have an elongated body bearing 6-15 pairs of **gill slits** for respiration. Cyclostomes have a sucking and circular mouth without jaws (Fig. 4.18). Their body is devoid of scales and paired fins. Cranium and vertebral column are cartilaginous. Circulation is of closed type. Cyclostomes are marine but migrate for spawning to fresh water. After spawning, within a few days, they die. Their larvae, after metamorphosis, return to the ocean.

Examples: *Petromyzon* (Lamprey) and *Myxine* (Hagfish).

Figure 4.18 A jawless vertebrate - *Petromyzon*

4.2.11.2 Class – Chondrichthyes

They are marine animals with streamlined body and have cartilaginous endoskeleton (Figure 4.19). Mouth is located ventrally. **Notochord** is **persistent** throughout life. Gill slits are separate and without **operculum** (gill cover). The skin is tough, containing minute **placoid scales**. Teeth are modified placoid scales which are backwardly directed. Their jaws are very powerful. These animals are predaceous. Due to the absence of air bladder, they have to swim constantly to avoid sinking.

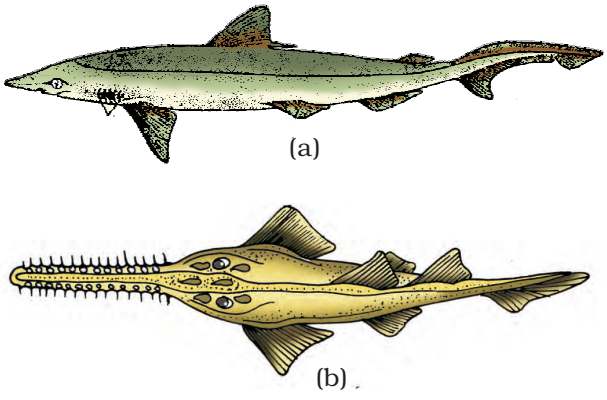


Figure 4.19 Example of Cartilaginous fishes : (a) *Scoliodon* (b) *Pristis*

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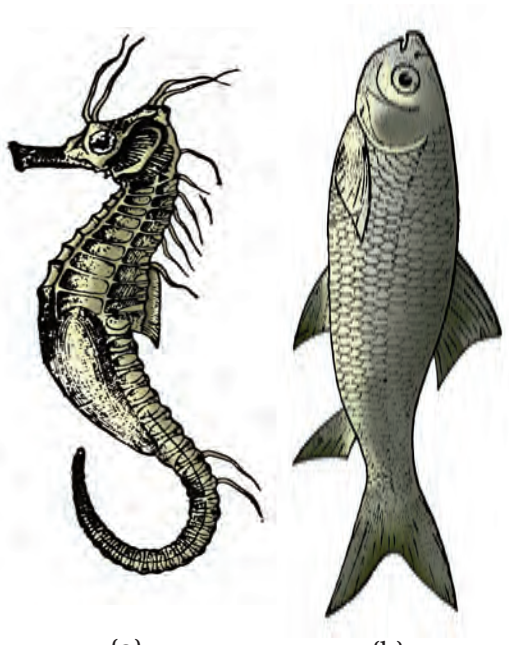
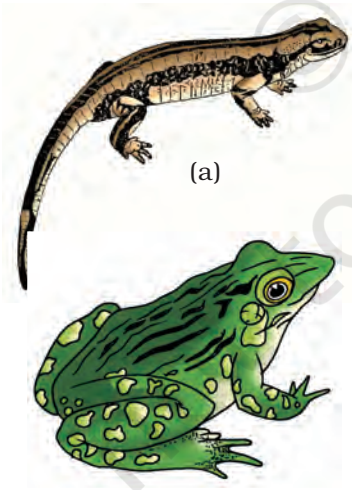


(a) (b)

Figure 4.20 Examples of Bony fishes : (a) *Hippocampus* (b) *Catla*



(a)

(b)

Figure 4.21 Examples of Amphibia : (a) *Salamandra* (b) *Rana*

Heart is two-chambered (one auricle and one ventricle). Some of them have **electric organs** (e.g., *Torpedo*) and some possess **poison sting** (e.g., *Trygon*). They are cold-blooded (**poikilothermous**) animals, i.e., they lack the capacity to regulate their body temperature. Sexes are separate. In males pelvic fins bear claspers. They have internal fertilisation and many of them are viviparous.

Examples: *Scoliodon* (Dog fish), *Pristis* (Saw fish), *Carcharodon* (Great white shark), *Trygon* (Sting ray).

4.2.11.3 Class – Osteichthyes

It includes both marine and fresh water fishes with bony endoskeleton. Their body is streamlined. Mouth is mostly terminal (Figure 4.20). They have four pairs of gills which are covered by an **operculum** on each side. Skin is covered with cycloid/ctenoid scales. **Air bladder** is present which regulates buoyancy. Heart is two-chambered (one auricle and one ventricle). They are cold-blooded animals. Sexes are separate. Fertilisation is usually external. They are mostly oviparous and development is direct.

Examples: Marine – *Exocoetus* (Flying fish), *Hippocampus* (Sea horse); Freshwater – *Labeo* (Rohu), *Catla* (Katla), *Clarias* (Magur); Aquarium – *Betta* (Fighting fish), *Pterophyllum* (Angel fish).

4.2.11.4 Class – Amphibia

As the name indicates (*Gr., Amphi* : dual, *bios*, life), amphibians can live in aquatic as well as terrestrial habitats (Figure 4.21). Most of them have two pairs of limbs. Body is divisible into **head** and **trunk.** Tail may be present in some. The amphibian skin is moist (without scales). The eyes have eyelids. A **tympanum** represents the ear. Alimentary canal, urinary and reproductive tracts open into a common chamber called **cloaca** which opens to the exterior. Respiration is by gills, lungs and through skin. The heart is three-chambered (two auricles and one ventricle). These are cold-blooded animals. Sexes are separate. Fertilisation is external. They are oviparous and development is indirect.

Examples: *Bufo* (Toad), *Rana* (Frog), *Hyla* (Tree frog), *Salamandra* (Salamander), *Ichthyophis* (Limbless amphibia).

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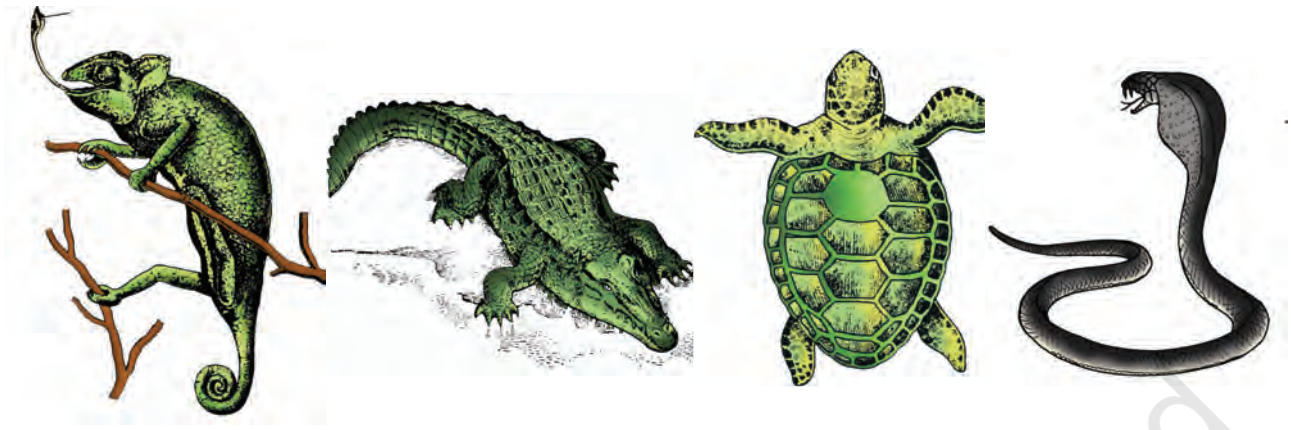

(a) (b) (c) (d)

Figure 4.22 Reptiles: (a) *Chameleon* (b) *Crocodilus* (c) *Chelone* (d) *Naja*

4.2.11.5 Class – Reptilia

The class name refers to their creeping or crawling mode of locomotion (*Latin*, *repere* or *reptum*, to creep or crawl). They are mostly terrestrial animals and their body is covered by dry and cornified skin, epidermal **scales** or **scutes** (Fig. 4.22). They do not have external ear openings. Tympanum represents ear. Limbs, when present, are two pairs. Heart is usually three-chambered, but four-chambered in crocodiles. Reptiles are poikilotherms. Snakes and lizards shed their scales as skin cast. Sexes are separate. Fertilisation is internal. They are oviparous and development is direct.

Examples: *Chelone* (Turtle), *Testudo* (Tortoise), *Chameleon* (Tree lizard), *Calotes* (Garden lizard), *Crocodilus* (Crocodile), *Alligator* (Alligator). *Hemidactylus* (Wall lizard), Poisonous snakes – *Naja* (Cobra), *Bangarus* (Krait), *Vipera* (Viper).

4.2.11.6 Class – Aves

The characteristic features of Aves (birds) are the presence of **feathers** and most of them can fly except flightless birds (e.g., Ostrich). They possess **beak** (Figure 4.23). The forelimbs are modified into **wings**. The hind limbs generally have scales and are modified for walking, swimming or clasping the tree branches. Skin is dry without glands except the oil gland at the base of the tail. Endoskeleton is fully ossified (bony) and the long bones are hollow with **air cavities** (pneumatic). The digestive tract of birds has additional chambers, the crop and gizzard. Heart is completely four-chambered. They are warm-blooded (**homoiothermous**) animals, i.e., they are able to maintain a constant body temperature. Respiration is by

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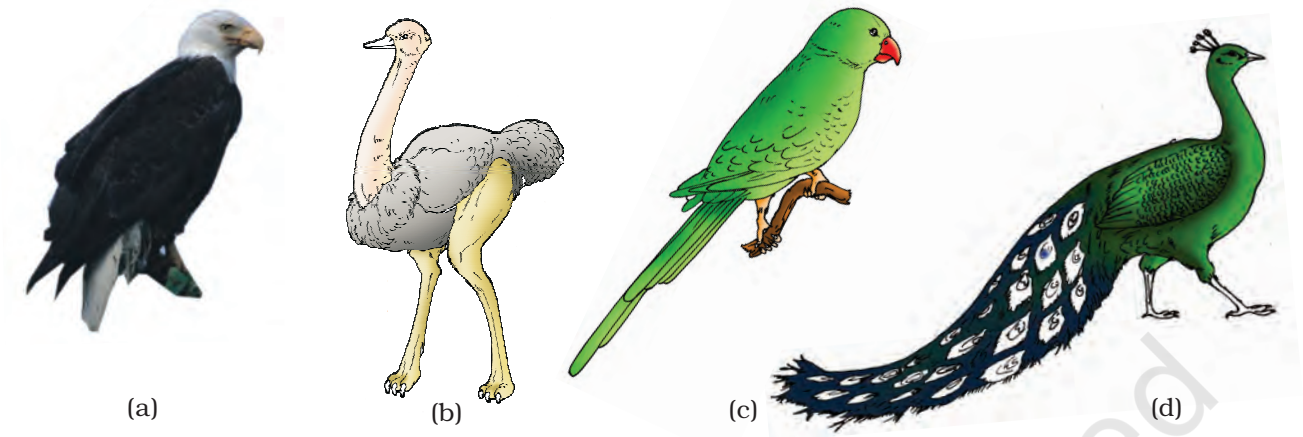

Figure 4.23 Some birds : (a) *Neophron* (b) *Struthio* (c) *Psittacula* (d) *Pavo*

lungs. Air sacs connected to lungs supplement respiration. Sexes are separate. Fertilisation is internal. They are oviparous and development is direct.

Examples : *Corvus* (Crow), *Columba* (Pigeon), *Psittacula* (Parrot), *Struthio* (Ostrich), *Pavo* (Peacock), *Aptenodytes* (Penguin), *Neophron* (Vulture).

4.2.11.7 Class – Mammalia

They are found in a variety of habitats – polar ice caps, deserts, mountains, forests, grasslands and dark caves. Some of them have adapted to fly or live in water. The most unique mammalian characteristic is the presence of milk producing glands (**mammary glands**) by which the young ones are nourished. They have two pairs of limbs, adapted for walking, running, climbing, burrowing, swimming or flying (Figure 4.24). The skin of

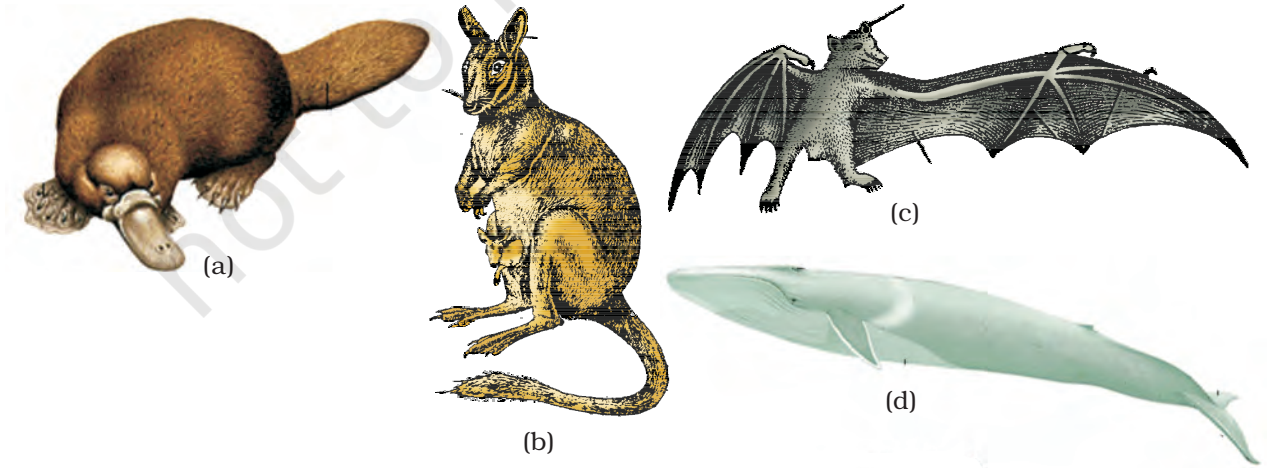

Figure 4.24 Some mammals : (a) *Ornithorhynchus* (b) *Macropus* (c) *Pteropus* (d) *Balaenoptera*

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mammals is unique in possessing **hair**. External ears or **pinnae** are present. Different types of teeth are present in the jaw. Heart is four-chambered. They are homoiothermous. Respiration is by lungs. Sexes are separate and fertilisation is internal. They are viviparous with few exceptions and development is direct.

Examples: Oviparous-*Ornithorhynchus* (Platypus); Viviparous - *Macropus* (Kangaroo), *Pteropus* (Flying fox), *Camelus* (Camel), *Macaca* (Monkey), *Rattus* (Rat), *Canis* (Dog), *Felis* (Cat), *Elephas* (Elephant), *Equus* (Horse), *Delphinus* (Common dolphin), *Balaenoptera* (Blue whale), *Panthera tigris* (Tiger), *Panthera leo* (Lion).

The salient distinguishing features of all phyla under animal kingdom is comprehensively given in the Table 4.2.

TABLE 4.2 Salient Features of Different Phyla in the Animal Kingdom

Phylum	Level of Organisation	Symmetry	Coelom	Segmentation	Digestive System	Circulatory System	Respiratory System	Distinctive Features
Porifera	Cellular	Various	Absent	Absent	Absent	Absent	Absent	Body with pores and canals in walls.
Coelenterata (Cnidaria)	Tissue	Radial	Absent	Absent	Incomplete	Absent	Absent	Cnidoblasts present.
Ctenophora	Tissue	Radial	Absent	Absent	Incomplete	Absent	Absent	Comb plates for locomotion.
Platyhelminthes	Organ & Organ-system	Bilateral	Absent	Absent	Incomplete	Absent	Absent	Flat body, suckers.
Aschelminthes	Organ-system	Bilateral	Pseudo coelomate	Absent	Complete	Absent	Absent	Often worm-shaped, elongated.
Annelida	Organ-system	Bilateral	Coelomate	Present	Complete	Present	Absent	Body segmentation like rings.
Arthropoda	Organ-system	Bilateral	Coelomate	Present	Complete	Present	Present	Exoskeleton of cuticle, jointed appendages.
Mollusca	Organ-system	Bilateral	Coelomate	Absent	Complete	Present	Present	External skeleton of shell usually present.
Echinodermata	Organ-system	Radial	Coelomate	Absent	Complete	Present	Present	Water vascular system, radial symmetry.
Hemichordata	Organ-system	Bilateral	Coelomate	Absent	Complete	Present	Present	Worm-like with proboscis, collar and trunk.
Chordata	Organ-system	Bilateral	Coelomate	Present	Complete	Present	Present	Notochord, dorsal hollow nerve cord, gill slits with limbs or fins.

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SUMMARY

The basic fundamental features such as level of organisation, symmetry, cell organisation, coelom, segmentation, notochord, etc., have enabled us to broadly classify the animal kingdom. Besides the fundamental features, there are many other distinctive characters which are specific for each phyla or class.

Porifera includes multicellular animals which exhibit cellular level of organisation and have characteristic flagellated choanocytes. The coelenterates have tentacles and bear cnidoblasts. They are mostly aquatic, sessile or free-floating. The ctenophores are marine animals with comb plates. The platyhelminths have flat body and exhibit bilateral symmetry. The parasitic forms show distinct suckers and hooks. Aschelminthes are pseudocoelomates and include parasitic as well as non-parasitic roundworms.

Annelids are metamerically segmented animals with a true coelom. The arthropods are the most abundant group of animals characterised by the presence of jointed appendages. The molluscs have a soft body surrounded by an external calcareous shell. The body is covered with external skeleton made of chitin. The echinoderms possess a spiny skin. Their most distinctive feature is the presence of water vascular system. The hemichordates are a small group of worm-like marine animals. They have a cylindrical body with proboscis, collar and trunk.

Phylum Chordata includes animals which possess a notochord either throughout or during early embryonic life. Other common features observed in the chordates are the dorsal, hollow nerve cord and paired pharyngeal gill slits. Some of the vertebrates do not possess jaws (Agnatha) whereas most of them possess jaws (Gnathostomata). Agnatha is represented by the class, Cyclostomata. They are the most primitive chordates and are ectoparasites on fishes. Gnathostomata has two super classes, Pisces and Tetrapoda. Classes Chondrichthyes and Osteichthyes bear fins for locomotion and are grouped under Pisces. The Chondrichthyes are fishes with cartilaginous endoskeleton and are marine. Classes, Amphibia, Reptilia, Aves and Mammalia have two pairs of limbs and are thus grouped under Tetrapoda. The amphibians have adapted to live both on land and water. Reptiles are characterised by the presence

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of dry and cornified skin. Limbs are absent in snakes. Fishes, amphibians and reptiles are poikilothermous (cold-blooded). Aves are warm-blooded animals with feathers on their bodies and forelimbs modified into wings for flying. Hind limbs are adapted for walking, swimming, perching or clasping. The unique features of mammals are the presence of mammary glands and hairs on the skin. They commonly exhibit viviparity.

EXERCISES

1. What are the difficulties that you would face in classification of animals, if common fundamental features are not taken into account?
2. If you are given a specimen, what are the steps that you would follow to classify it?
3. How useful is the study of the nature of body cavity and coelom in the classification of animals?
4. Distinguish between intracellular and extracellular digestion?
5. What is the difference between direct and indirect development?
6. What are the peculiar features that you find in parasitic platyhelminthes?
7. What are the reasons that you can think of for the arthropods to constitute the largest group of the animal kingdom?
8. Water vascular system is the characteristic of which group of the following:

   (a) Porifera (b) Ctenophora (c) Echinodermata (d) Chordata
9. "All vertebrates are chordates but all chordates are not vertebrates". Justify the statement.
10. How important is the presence of air bladder in Pisces?
11. What are the modifications that are observed in birds that help them fly?
12. Could the number of eggs or young ones produced by an oviparous and viviparous mother be equal? Why?
13. Segmentation in the body is first observed in which of the following:

    (a) Platyhelminthes (b) Aschelminthes (c) Annelida (d) Arthropoda

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14. Match the following:

(a)	Operculum	(i)	Ctenophora
(b)	Parapodia	(ii)	Mollusca
(c)	Scales	(iii)	Porifera
(d)	Comb plates	(iv)	Reptilia
(e)	Radula	(v)	Annelida
(f)	Hairs	(vi)	Cyclostomata and Chondrichthyes
(g)	Choanocytes	(vii)	Mammalia
(h)	Gill slits	(viii)	Osteichthyes

15. Prepare a list of some animals that are found parasitic on human beings.

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UNIT 2

STRUCTURAL ORGANISATION IN PLANTS AND ANIMALS

Chapter 5
Morphology of Flowering Plants

Chapter 6
Anatomy of Flowering Plants

Chapter 7
Structural Organisation in Animals

The description of the diverse forms of life on earth was made only by observation – through naked eyes or later through magnifying lenses and microscopes. This description is mainly of gross structural features, both external and internal. In addition, observable and perceivable living phenomena were also recorded as part of this description. Before experimental biology or more specifically, physiology, was established as a part of biology, naturalists described only biology. Hence, biology remained as a natural history for a long time. The description, by itself, was amazing in terms of detail. While the initial reaction of a student could be boredom, one should keep in mind that the detailed description, was utilised in the later day reductionist biology where living processes drew more attention from scientists than the description of life forms and their structure. Hence, this description became meaningful and helpful in framing research questions in physiology or evolutionary biology. In the following chapters of this unit, the structural organisation of plants and animals, including the structural basis of physiologial or behavioural phenomena, is described. For convenience, this description of morphological and anatomical features is presented separately for plants and animals.

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Katherine Esau
(1898 – 1997)

KATHERINE ESAU was born in Ukraine in 1898. She studied agriculture in Russia and Germany and received her doctorate in 1931 in United States. She reported in her early publications that the curly top virus spreads through a plant via the food-conducting or phloem tissue. Dr Esau's *Plant Anatomy* published in 1954 took a dynamic, developmental approach designed to enhance one's understanding of plant structure and an enormous impact worldwide, literally bringing about a revival of the discipline. The *Anatomy of Seed Plants* by Katherine Esau was published in 1960. It was referred to as Webster's of plant biology – it is encyclopediac. In 1957 she was elected to the National Academy of Sciences, becoming the sixth woman to receive that honour. In addition to this prestigious award, she received the National Medal of Science from President George Bush in 1989.

When Katherine Esau died in the year 1997, Peter Raven, director of Anatomy and Morphology, Missouri Botanical Garden, remembered that she 'absolutely dominated' the field of plant biology even at the age of 99.

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Chapter 5
Morphology of Flowering Plants

5.1 *The Root*

5.2 *The Stem*

5.3 *The Leaf*

5.4 *The Inflorescence*

5.5 *The Flower*

5.6 *The Fruit*

5.7 *The Seed*

5.8 *Semi-technical Description of a Typical Flowering Plant*

5.9 *Description of Some Important Families*

The wide range in the structure of higher plants will never fail to fascinate us. Even though the angiosperms show such a large diversity in external structure or **morphology**, they are all characterised by presence of roots, stems, leaves, flowers and fruits.

In chapters 2 and 3, we talked about classification of plants based on morphological and other characteristics. For any successful attempt at classification and at understanding any higher plant (or for that matter any living organism) we need to know standard technical terms and standard definitions. We also need to know about the possible variations in different parts, found as adaptations of the plants to their environment, e.g., adaptions to various habitats, for protection, climbing, storage, etc.

If you pull out any weed you will see that all of them have roots, stems and leaves. They may be bearing flowers and fruits. The underground part of the flowering plant is the root system while the portion above the ground forms the shoot system (Figure 5.1).

5.1 The Root

In majority of the dicotyledonous plants, the direct elongation of the radicle leads to the formation of **primary root** which grows inside the soil. It bears lateral roots of several orders that are referred to as **secondary, tertiary,** etc. **roots.** The primary roots and its branches constitute the

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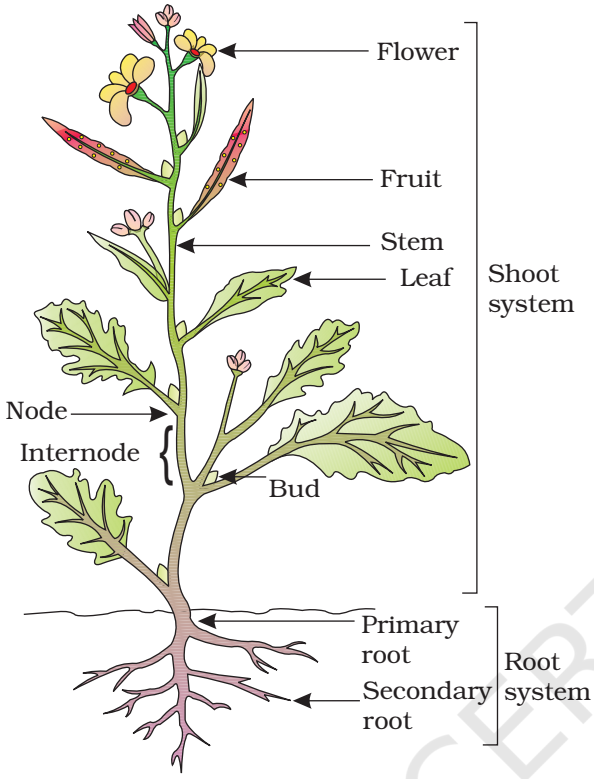

Figure 5.1 Parts of a flowering plant

tap root system, as seen in the mustard plant (Figure 5.2a). In monocotyledonous plants, the primary root is short lived and is replaced by a large number of roots. These roots originate from the base of the stem and constitute the **fibrous root system**, as seen in the wheat plant (Figure 5.2b). In some plants, like grass, *Monstera* and the banyan tree, roots arise from parts of the plant other than the radicle and are called **adventitious roots** (Figure 5.2c). The main functions of the root system are absorption of water and minerals from the soil, providing a proper anchorage to the plant parts, storing reserve food material and synthesis of plant growth regulators.

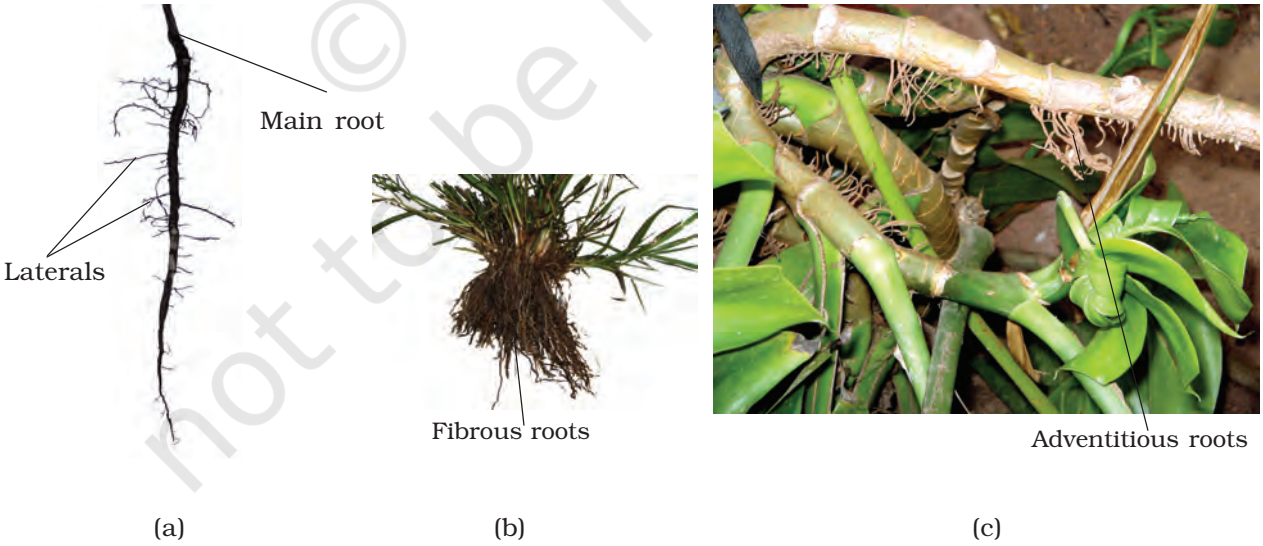

Figure 5.2 Different types of roots : (a) Tap (b) Fibrous (c) Adventitious

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5.1.1 Regions of the Root

The root is covered at the apex by a thimble-like structure called the **root cap** (Figure 5.3)**.** It protects the tender apex of the root as it makes its way through the soil. A few millimetres above the root cap is the **region of meristematic activity**. The cells of this region are very small, thin-walled and with dense protoplasm. They divide repeatedly. The cells proximal to this region undergo rapid elongation and enlargement and are responsible for the growth of the root in length. This region is called the **region of elongation**. The cells of the elongation zone gradually differentiate and mature. Hence, this zone, proximal to region of elongation, is called the **region of maturation**. From this region some of the epidermal cells form very fine and delicate, thread-like structures called **root hairs**. These root hairs absorb water and minerals from the soil.

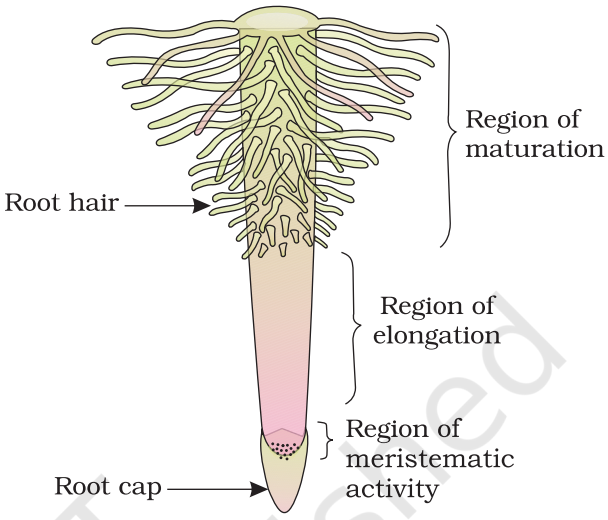

Figure 5.3 The regions of the root-tip

5.2 THE STEM

What are the features that distinguish a stem from a root? The stem is the ascending part of the axis bearing branches, leaves, flowers and fruits. It develops from the plumule of the embryo of a germinating seed. The stem bears **nodes** and **internodes**. The region of the stem where leaves are born are called nodes while internodes are the portions between two nodes. The stem bears buds, which may be terminal or axillary. Stem is generally green when young and later often become woody and dark brown.

The main function of the stem is spreading out branches bearing leaves, flowers and fruits. It conducts water, minerals and photosynthates. Some stems perform the function of storage of food, support, protection and of vegetative propagation.

5.3 THE LEAF

The leaf is a lateral, generally flattened structure borne on the stem. It develops at the node and bears a bud in its axil. The **axillary bud** later develops into a branch. Leaves originate from shoot apical meristems and are arranged in an acropetal order. They are the most important vegetative organs for photosynthesis.

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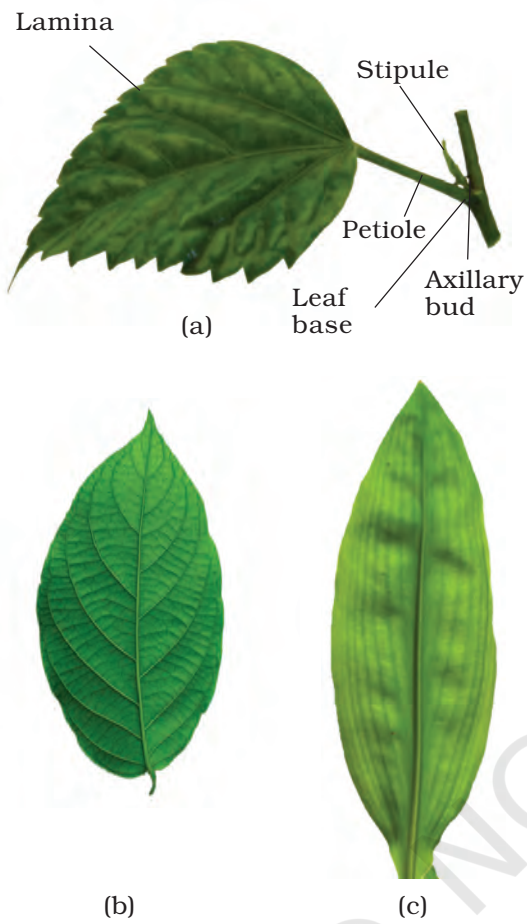

Figure 5.4 Structure of a leaf :
(a) Parts of a leaf
(b) Reticulate venation
(c) Parallel venation

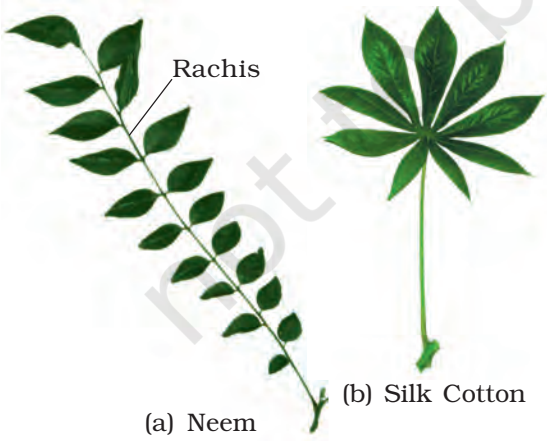

Figure 5.5 Compound leaves :
(a) pinnately compound leaf
(b) palmately compound leaf

A typical leaf consists of three main parts: leaf base, petiole and lamina (Figure 5.4 a). The leaf is attached to the stem by the **leaf base** and may bear two lateral small leaf like structures called stipules. In monocotyledons, the leaf base expands into a sheath covering the stem partially or wholly. In some leguminous plants the leafbase may become swollen, which is called the **pulvinus**. The **petiole** help hold the blade to light. Long thin flexible petioles allow leaf blades to flutter in wind, thereby cooling the leaf and bringing fresh air to leaf surface. The **lamina** or the **leaf blade** is the green expanded part of the leaf with veins and veinlets. There is, usually, a middle prominent vein, which is known as the midrib. Veins provide rigidity to the leaf blade and act as channels of transport for water, minerals and food materials. The shape, margin, apex, surface and extent of incision of lamina varies in different leaves.

5.3.1 Venation

The arrangement of veins and the veinlets in the lamina of leaf is termed as **venation**. When the veinlets form a network, the venation is termed as **reticulate** (Figure 5.4 b). When the veins run parallel to each other within a lamina, the venation is termed as **parallel** (Figure 5.4 c). Leaves of dicotyledonous plants generally possess reticulate venation, while parallel venation is the characteristic of most monocotyledons.

5.3.2 Types of Leaves

A leaf is said to be **simple**, when its lamina is entire or when incised, the incisions do not touch the midrib. When the incisions of the lamina reach up to the midrib breaking it into a number of leaflets, the leaf is called **compound**. A bud is present in the axil of petiole in both simple and compound leaves, but not in the axil of leaflets of the compound leaf.

The compound leaves may be of two types (Figure 5.5). In a **pinnately compound leaf** a

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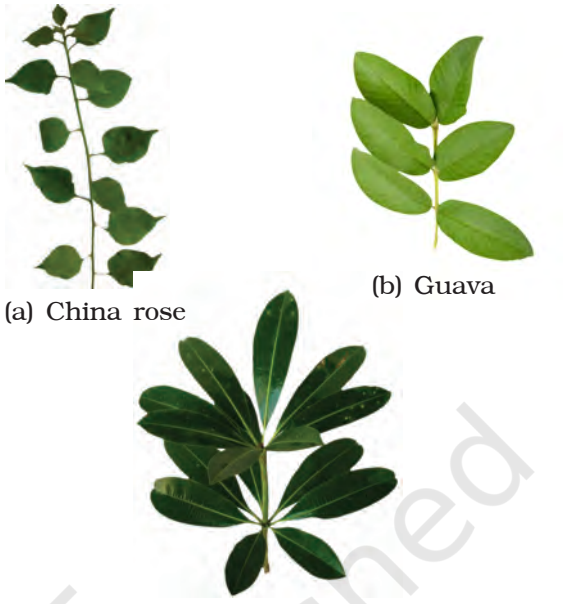
number of leaflets are present on a common axis, the **rachis**, which represents the midrib of the leaf as in neem.

In **palmately compound leaves,** the leaflets are attached at a common point, i.e., at the tip of petiole, as in silk cotton.

5.3.3 Phyllotaxy

Phyllotaxy is the pattern of arrangement of leaves on the stem or branch. This is usually of three types – alternate, opposite and whorled (Figure 5.6). In **alternate** type of phyllotaxy, a single leaf arises at each node in alternate manner, as in china rose, mustard and sun flower plants. In **opposite** type, a pair of leaves arise at each node and lie opposite to each other as in *Calotropis* and guava plants. If more than two leaves arise at a node and form a whorl, it is called **whorled,** as in *Alstonia.*



(a) China rose (b) Guava (c) Alstonia

Figure 5.6 Different types of phyllotaxy : (a) Alternate (b) Opposite (c) Whorled

5.4 THE INFLORESCENCE

A flower is a modified shoot wherein the shoot apical meristem changes to floral meristem. Internodes do not elongate and the axis gets condensed. The apex produces different kinds of floral appendages laterally at successive nodes instead of leaves. When a shoot tip transforms into a flower, it is always solitary. The arrangement of flowers on the floral axis is termed as **inflorescence**. Depending on whether the apex gets developed into a flower or continues to grow, two major types of inflorescences are defined – racemose and cymose. In **racemose** type of inflorescences the main axis continues to grow, the flowers are borne laterally in an acropetal succession (Figure 5.7).

In **cymose** type of inflorescence the main axis terminates in a flower, hence is limited in growth.The flowers are borne in a basipetal order (Figure 5.8).

Figure 5.7 Racemose inflorescence

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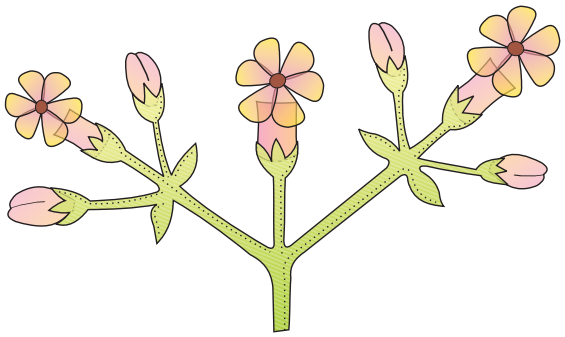


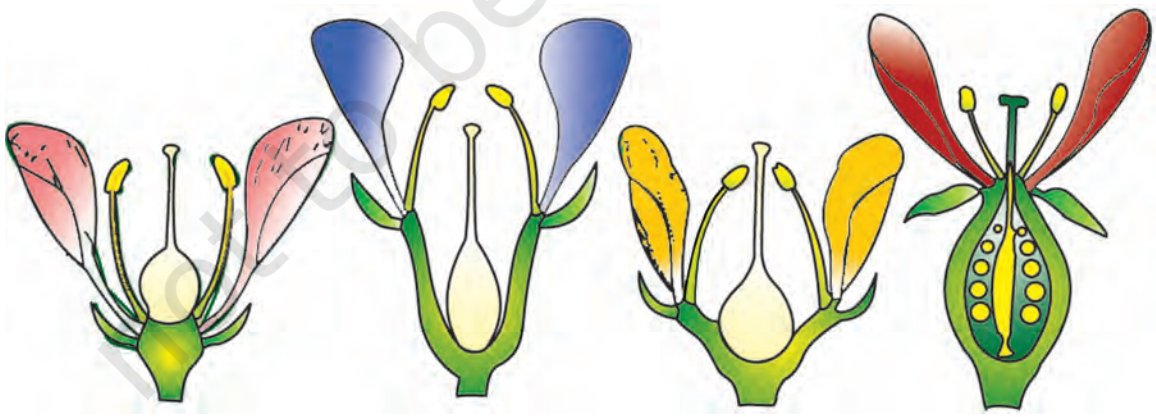
Figure 5.8 Cymose inflorescence

5.5 THE FLOWER

The flower is the reproductive unit in the angiosperms. It is meant for sexual reproduction. A typical flower has four different kinds of whorls arranged successively on the swollen end of the stalk or pedicel, called **thalamus or receptacle**. These are calyx, corolla, androecium and gynoecium. Calyx and corolla are accessory organs, while androecium and gynoecium are reproductive organs. In some flowers like lily, the calyx and corolla are not distinct and are termed as perianth. When a flower has both androecium and gynoecium, it is **bisexual**. A flower having either only stamens or only carpels is **unisexual.**

In symmetry, the flower may be **actinomorphic** (radial symmetry) or **zygomorphic** (bilateral symmetry). When a flower can be divided into two equal radial halves in any radial plane passing through the centre, it is said to be **actinomorphic,** e.g., mustard, *datura*, chilli. When it can be divided into two similar halves only in one particular vertical plane, it is **zygomorphic,** e.g., pea, gulmohur, bean, *Cassia*. A flower is **asymmetric** (irregular) if it cannot be divided into two similar halves by any vertical plane passing through the centre, as in canna.

A flower may be **trimerous, tetramerous** or **pentamerous** when the floral appendages are in multiple of 3, 4 or 5, respectively. Flowers with bracts - reduced leaf found at the base of the pedicel - are called **bracteate** and those without bracts, **ebracteate**.



(a) (b) (c) (d)

Figure 5.9 Position of floral parts on thalamus : (a) Hypogynous (b) and (c) Perigynous (d) Epigynous

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Based on the position of calyx, corolla and androecium in respect of the ovary on thalamus, the flowers are described as hypogynous, perigynous and epigynous (Figure 5.9). In the **hypogynous** flower the gynoecium occupies the highest position while the other parts are situated below it. The ovary in such flowers is said to be **superior,** e.g., mustard, china rose and brinjal. If gynoecium is situated in the centre and other parts of the flower are located on the rim of the thalamus almost at the same level, it is called **perigynous.** The ovary here is said to be **half inferior,** e.g., plum, rose, peach. In **epigynous flowers,** the margin of thalamus grows upward enclosing the ovary completely and getting fused with it, the other parts of flower arise above the ovary. Hence, the ovary is said to be **inferior** as in flowers of guava and cucumber, and the ray florets of sunflower.

5.5.1 Parts of a Flower

Each flower normally has four floral whorls, viz., calyx, corolla, androecium and gynoecium (Figure 5.10).

5.5.1.1 Calyx

The calyx is the outermost whorl of the flower and the members are called sepals. Generally, sepals are green, leaf like and protect the flower in the bud stage. The calyx may be **gamosepalous** (sepals united) or **polysepalous** (sepals free).

5.5.1.2 Corolla

Corolla is composed of petals. Petals are usually brightly coloured to attract insects for pollination. Like calyx, corolla may also be **gamopetalous** (petals united) or **polypetalous** (petals free). The shape and colour of corolla vary greatly in plants. Corolla may be tubular, bell-shaped, funnel-shaped or wheel-shaped.

Aestivation: The mode of arrangement of sepals or petals in floral bud with respect to the other members of the same whorl is known as aestivation. The main types of aestivation are valvate, twisted, imbricate

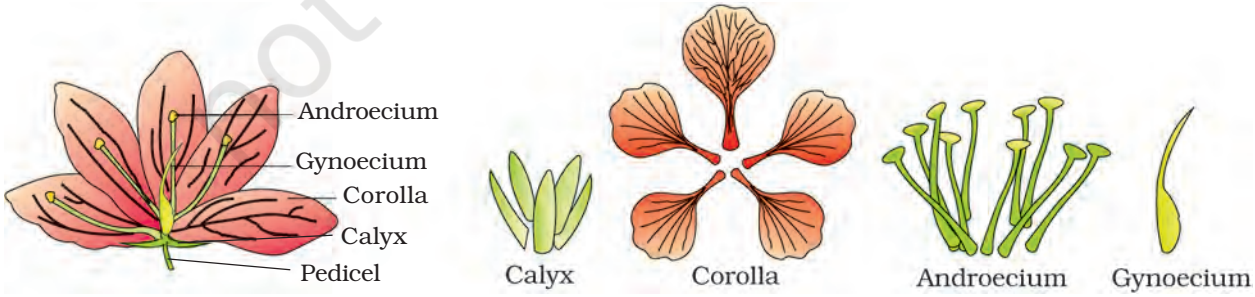

Figure 5.10 Parts of a flower

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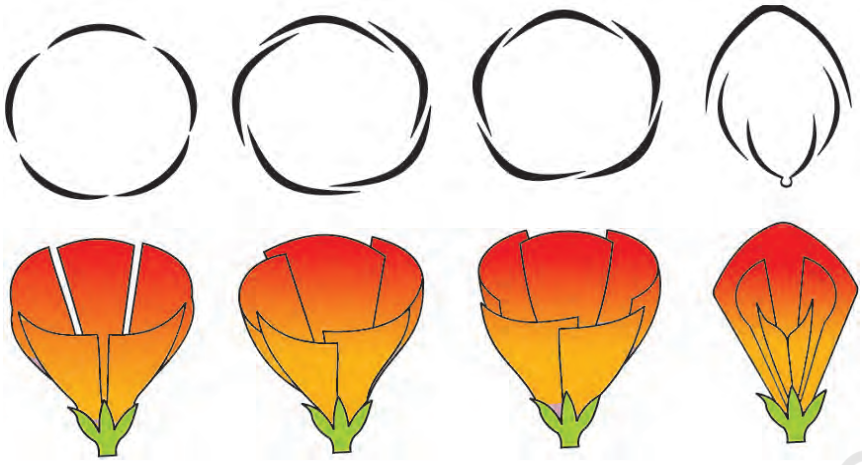

Figure 5.11 Types of aestivation in corolla : (a) Valvate (b) Twisted (c) Imbricate (d) Vexillary

and vexillary (Figure 5.11). When sepals or petals in a whorl just touch one another at the margin, without overlapping, as in *Calotropis*, it is said to be **valvate.** If one margin of the appendage overlaps that of the next one and so on as in china rose, lady's finger and cotton, it is called **twisted**. If the margins of sepals or petals overlap one another but not in any particular direction as in *Cassia* and gulmohur, the aestivation is called **imbricate**. In pea and bean flowers, there are five petals, the largest (standard) overlaps the two lateral petals (wings) which in turn overlap the two smallest anterior petals (keel); this type of aestivation is known as **vexillary** or papilionaceous.

5.5.1.3 Androecium

Androecium is composed of stamens. Each stamen which represents the male reproductive organ consists of a stalk or a filament and an anther. Each anther is usually bilobed and each lobe has two chambers, the pollen-sacs. The pollen grains are produced in pollen-sacs. A sterile stamen is called **staminode**.

Stamens of flower may be united with other members such as petals or among themselves. When stamens are attached to the petals, they are **epipetalous** as in brinjal, or **epiphyllous** when attached to the perianth as in the flowers of lily. The stamens in a flower may either remain free (polyandrous) or may be united in varying degrees. The stamens may be united into one bunch or one bundle **(monoadelphous)** as in china rose, or two bundles **(diadelphous)** as in pea, or into more than two bundles **(polyadelphous)** as in citrus. There may be a variation in the length of filaments within a flower, as in *Salvia* and mustard.

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5.5.1.4 *Gynoecium*

Gynoecium is the female reproductive part of the flower and is made up of one or more carpels. A carpel consists of three parts namely stigma, style and ovary. **Ovary** is the enlarged basal part, on which lies the elongated tube, the style. The style connects the ovary to the stigma. The **stigma** is usually at the tip of the **style** and is the receptive surface for pollen grains. Each ovary bears one or more ovules attached to a flattened, cushion-like **placenta**. When more than one carpel is present, they may be free (as in lotus and rose) and are called **apocarpous**. They are termed **syncarpous** when carpels are fused, as in mustard and tomato. After fertilisation, the ovules develop into seeds and the ovary matures into a fruit.

Placentation: The arrangement of ovules within the ovary is known as placentation. The placentation are of different types namely, marginal, axile, parietal, basal, central and free central (Figure 5.12). In **marginal** placentation the placenta forms a ridge along the ventral suture of the ovary and the ovules are borne on this ridge forming two rows, as in pea. When the placenta is axial and the ovules are attached to it in a multilocular ovary, the placentaion is said to be **axile**, as in china rose, tomato and lemon. In **parietal** placentation, the ovules develop on the inner wall of the ovary or on peripheral part. Ovary is one-chambered but it becomes two-chambered due to the formation of the false septum, e.g., mustard and *Argemone*. When the ovules are borne on central axis and septa are absent, as in *Dianthus* and *Primrose* the placentation is called **free central.** In **basal** placentation, the placenta develops at the base of ovary and a single ovule is attached to it, as in sunflower, marigold.

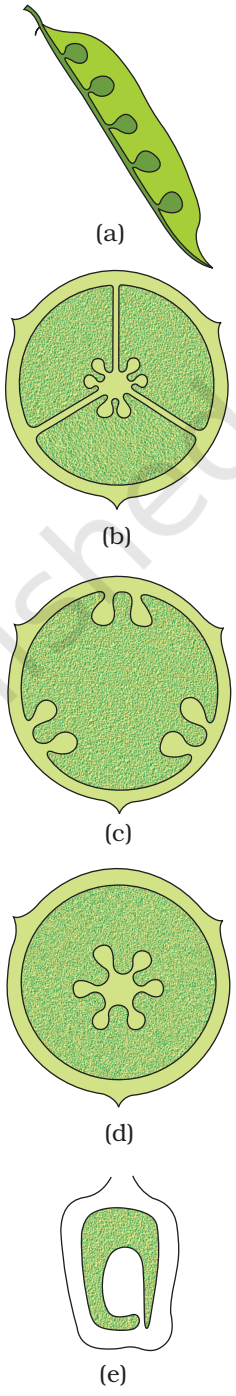

Figure 5.12 Types of placentation : (a) Marginal (b) Axile (c) Parietal (d) Free central (e) Basal

5.6 THE FRUIT

The fruit is a characteristic feature of the flowering plants. It is a mature or ripened ovary, developed after fertilisation. If a fruit is formed without fertilisation of the ovary, it is called a **parthenocarpic** fruit.

Generally, the fruit consists of a wall or **pericarp** and seeds. The pericarp may be dry or fleshy. When pericarp is thick and fleshy, it is differentiated into the outer **epicarp,** the middle **mesocarp** and the inner **endocarp**.

In mango and coconut, the fruit is known as a drupe (Figure 5.13). They develop from monocarpellary superior ovaries and are one seeded. In mango the pericarp is well differentiated into an

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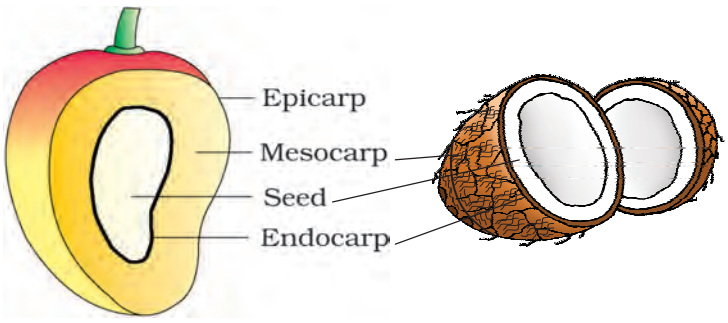

(a) (b)

Figure 5.13 Parts of a fruit : (a) Mango (b) Coconut

outer thin epicarp, a middle fleshy edible mesocarp and an inner stony hard endocarp. In coconut which is also a drupe, the mesocarp is fibrous.

5.7 The Seed

The ovules after fertilisation, develop into seeds. A seed is made up of a seed coat and an embryo. The embryo is made up of a radicle, an embryonal axis and one (as in wheat, maize) or two cotyledons (as in gram and pea).

5.7.1 Structure of a Dicotyledonous Seed

The outermost covering of a seed is the seed coat. The seed coat has two layers, the outer **testa** and the inner **tegmen**. The **hilum** is a scar on the seed coat through which the developing seeds were attached to the fruit. Above the hilum is a small pore called the **micropyle**. Within the seed coat is the embryo, consisting of an embryonal axis and two cotyledons. The cotyledons are often fleshy and full of reserve food materials. At the two ends of the embryonal axis are present the radicle and the plumule (Figure 5.14). In some seeds such as castor the **endosperm** formed as a result of double fertilisation, is a food storing tissue and called endospermic seeds. In plants such as bean, gram and pea, the endosperm is not present in mature seeds and such seeds are called non-endospermous.

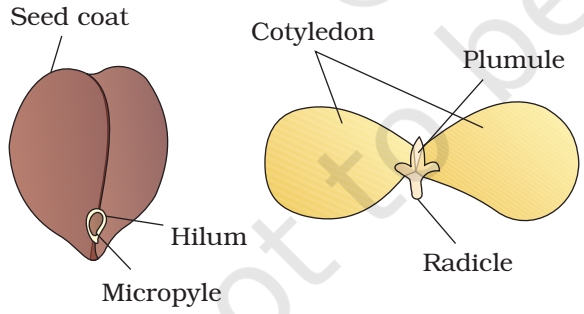

Figure 5.14 Structure of dicotyledonous seed

5.7.2 Structure of Monocotyledonous Seed

Generally, monocotyledonous seeds are endospermic but some as in orchids are non-endospermic. In the seeds of cereals such as maize the

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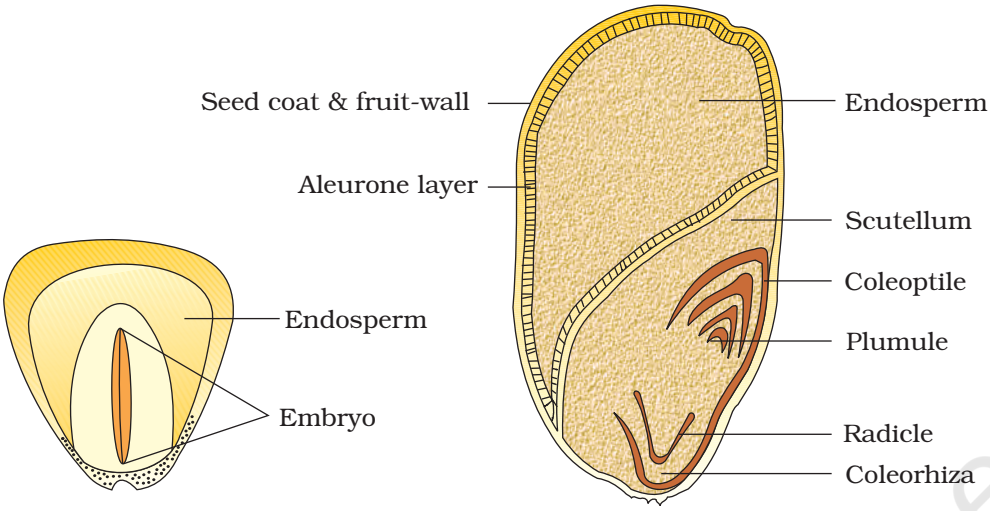
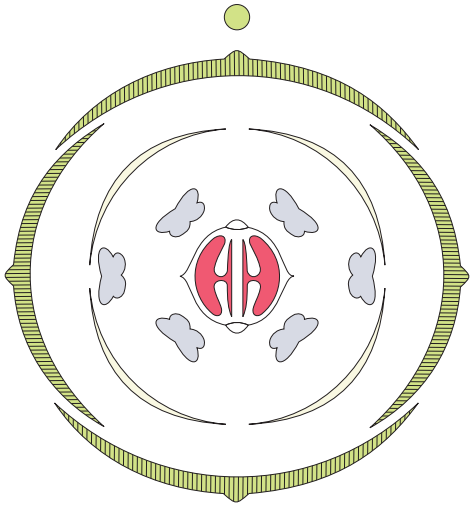


Figure 5.15 Structure of a monocotyledonous seed

seed coat is membranous and generally fused with the fruit wall. The endosperm is bulky and stores food. The outer covering of endosperm separates the embryo by a proteinous layer called **aleurone layer**. The embryo is small and situated in a groove at one end of the endosperm. It consists of one large and shield shaped cotyledon known as **scutellum** and a short axis with a **plumule** and a **radicle**. The plumule and radicle are enclosed in sheaths which are called **coleoptile** and **coleorhiza** respectively (Figure 5.15).

5.8 SEMI-TECHNICAL DESCRIPTION OF A TYPICAL FLOWERING PLANT

Various morphological features are used to describe a flowering plant. The description has to be brief, in a simple and scientific language and presented in a proper sequence. The plant is described beginning with its habit, vegetative characters – roots, stem and leaves and then floral characters inflorescence and flower parts. After describing various parts of plant, a floral diagram and a floral formula are presented. The floral formula is represented by some symbols. In the floral formula, **Br** stands for bracteate **K** stands for calyx , **C** for corolla, **P** for perianth, **A** for androecium and **G** for Gynoecium, $\underline{\mathbf{G}}$ for superior ovary and $\overline{\mathbf{G}}$ for inferior ovary, ♂ for male, ♀ for female, ⚥ for bisexual plants, ⊕ for actinomorphic



$\oplus$ ⚥ $K_{2+2}\,C_4\,A_{2+4}\,\underline{G}_{(2)}$

Figure 5.16 Floral diagram with floral formula

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and % for zygomorphic nature of flower. Fusion is indicated by enclosing the figure within bracket and adhesion by a line drawn above the symbols of the floral parts. A floral diagram provides information about the number of parts of a flower, their arrangement and the relation they have with one another (Figure 5.16). The position of the mother axis with respect to the flower is represented by a dot on the top of the floral diagram. Calyx, corolla, androecium and gynoecium are drawn in successive whorls, calyx being the outermost and the gynoecium being in the centre. Floral formula also shows cohesion and adhesion within parts of whorls and between whorls. The floral diagram and floral formula in Figure 5.16 represents the mustard plant (Family: Brassicaceae).

5.9 SOLANACEAE

It is a large family, commonly called as the 'potato family'. It is widely distributed in tropics, subtropics and even temperate zones (Figure 5.17).

Vegetative Characters

Plants mostly herbs, shrubs and rarely small trees

Stem: herbaceous rarely woody, aerial; erect, cylindrical, branched, solid or hollow, hairy or glabrous, underground stem in potato (*Solanum tuberosum*)

Leaves: alternate, simple, rarely pinnately compound, exstipulate; venation reticulate

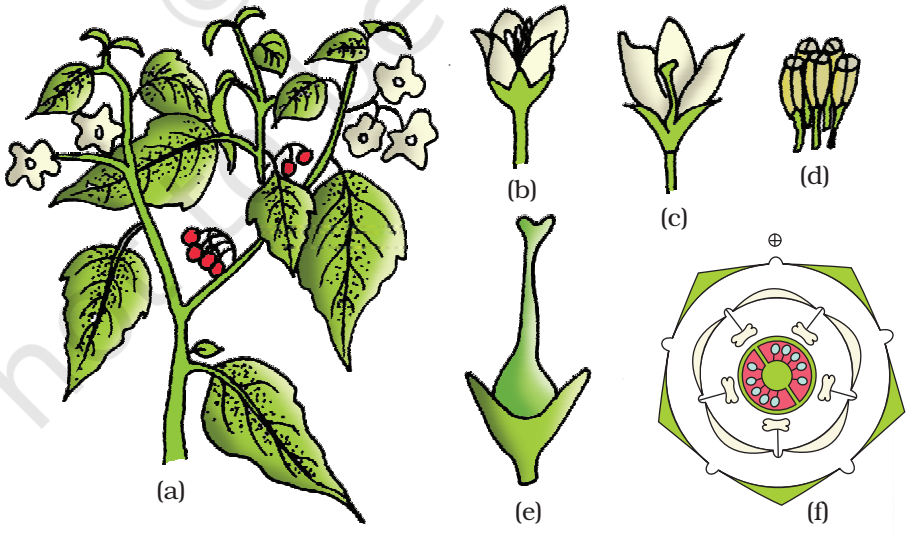

Figure 5.17 *Solanum nigrum* (makoi) plant : (a) Flowering twig (b) Flower (c) L.S. of flower (d) Stamens (e) Carpel (f) Floral diagram

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Floral Characters

Inflorescence : Solitary, axillary or cymose as in *Solanum*
Flower: bisexual, actinomorphic
Calyx: sepals five, united, persistent, valvate aestivation
Corolla: petals five, united; valvate aestivation
Androecium: stamens five, epipetalous
Gynoecium: bicarpellary obligately placed, syncarpous; ovary superior, bilocular, placenta swollen with many ovules, axile
Fruits: berry or capsule
Seeds: many, endospermous

Floral Formula: $\oplus \, ♀♂ \, K_{(5)} \, \overset{\frown}{C_{(5)}} \, A_5 \, \underline{G}_{(2)}$

Economic Importance

Many plants belonging to this family are source of food (tomato, brinjal, potato), spice (chilli); medicine (belladonna, *ashwagandha*); fumigatory (tobacco); ornamentals (petunia).

SUMMARY

Flowering plants exhibit enormous variation in shape, size, structure, mode of nutrition, life span, habit and habitat. They have well developed root and shoot systems. Root system is either tap root or fibrous. Generally, dicotyledonous plants have tap roots while monocotyledonous plants have fibrous roots. The roots in some plants get modified for storage of food, mechanical support and respiration. The shoot system is differentiated into stem, leaves, flowers and fruits. The morphological features of stems like the presence of nodes and internodes, multicellular hair and positively phototropic nature help to differentiate the stems from roots. Leaf is a lateral outgrowth of stem developed exogeneously at the node. These are green in colour to perform the function of photosynthesis. Leaves exhibit marked variations in their shape, size, margin, apex and extent of incisions of leaf blade (lamina).

The flower is a modified shoot, meant for sexual reproduction. The flowers are arranged in different types of inflorescences. They exhibit enormous variation in structure, symmetry, position of ovary in relation to other parts, arrangement of petals, sepals, ovules etc. After fertilisation, the ovary is modified into fruits and ovules into seeds. Seeds either may be monocotyledonous or dicotyledonous. They vary in shape, size and period of viability. The floral characteristics form the basis of classification

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and identification of flowering plants. This can be illustrated through semi-technical descriptions of families. Hence, a flowering plant is described in a definite sequence by using scientific terms. The floral features are represented in the summarised form as floral diagrams and floral formula.

EXERCISES

1. How is a pinnately compound leaf different from a palmately compound leaf?
2. Explain with suitable examples the different types of phyllotaxy.
3. Define the following terms:
   (a) aestivation (b) placentation (c) actinomorphic
   (d) zygomorphic (e) superior ovary (f) perigynous flower
   (g) epipetalous stamen
4. Differentiate between
   (a) Racemose and cymose inflorescence
   (b) Apocarpous and syncarpous ovary
5. Draw the labelled diagram of the following:
   (i) gram seed (ii) V.S. of maize seed
6. Take one flower of the family Solanaceae and write its semi-technical description. Also draw their floral diagram.
7. Describe the various types of placentations found in flowering plants.
8. What is a flower? Describe the parts of a typical angiosperm flower.
9. Define the term inflorescence. Explain the basis for the different types inflorescence in flowering plants.
10. Describe the arrangement of floral members in relation to their insertion on thalamus.

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Chapter 6
Anatomy of Flowering Plants

6.1 *The Tissue System*

6.2 *Anatomy of Dicotyledonous and Monocotyledonous Plants*

You can very easily see the structural similarities and variations in the external morphology of the larger living organism, both plants and animals. Similarly, if we were to study the internal structure, one also finds several similarities as well as differences. This chapter introduces you to the internal structure and functional organisation of higher plants. Study of internal structure of plants is called anatomy. Plants have cells as the basic unit, cells are organised into tissues and in turn the tissues are organised into organs. Different organs in a plant show differences in their internal structure. Within angiosperms, the monocots and dicots are also seen to be anatomically different. Internal structures also show adaptations to diverse environments.

6.1 The Tissue System

We were discussing types of tissues based on the types of cells present. Let us now consider how tissues vary depending on their location in the plant body. Their structure and function would also be dependent on location. On the basis of their structure and location, there are three types of tissue systems. These are the epidermal tissue system, the ground or fundamental tissue system and the vascular or conducting tissue system.

6.1.1 Epidermal Tissue System

The epidermal tissue system forms the outer-most covering of the whole plant body and comprises epidermal cells, stomata and the epidermal appendages – the trichomes and hairs. The **epidermis** is the outermost layer of the primary plant body. It is made up of elongated, compactly

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arranged cells, which form a continuous layer. Epidermis is usually single-layered. Epidermal cells are parenchymatous with a small amount of cytoplasm lining the cell wall and a large vacuole. The outside of the epidermis is often covered with a waxy thick layer called the **cuticle** which prevents the loss of water. Cuticle is absent in roots. **Stomata** are structures present in the epidermis of leaves. Stomata regulate the process of transpiration and gaseous exchange. Each stoma is composed of two bean-shaped cells known as **guard cells** which enclose stomatal pore**.** In grasses, the guard cells are dumb-bell shaped. The outer walls of guard cells (away from the stomatal pore) are thin and the inner walls (towards the stomatal pore) are highly thickened. The guard cells possess chloroplasts and regulate the opening and closing of stomata. Sometimes, a few epidermal cells, in the vicinity of the guard cells become specialised in their shape and size and are known as **subsidiary cells**. The stomatal aperture, guard cells and the surrounding subsidiary cells are together called **stomatal apparatus** (Figure 6.1).

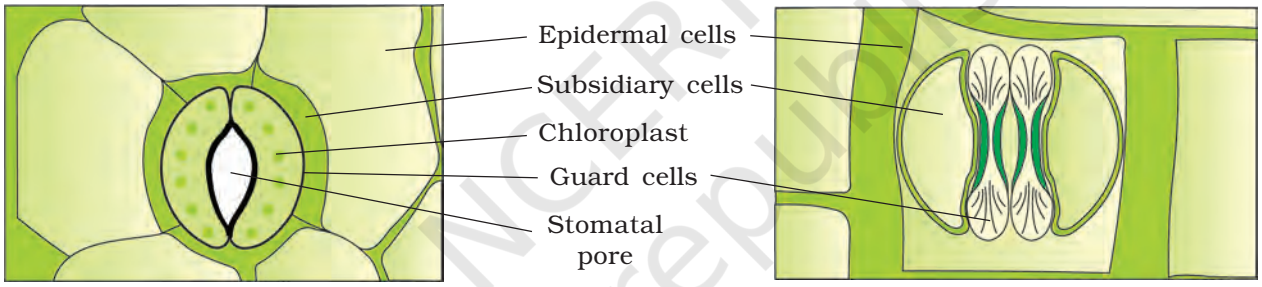

Figure 6.1 Diagrammatic representation: (a) stomata with bean-shaped guard cells (b) stomata with dumb-bell shaped guard cell

The cells of epidermis bear a number of hairs. The **root hairs** are unicellular elongations of the epidermal cells and help absorb water and minerals from the soil. On the stem the epidermal hairs are called **trichomes**. The trichomes in the shoot system are usually multicellular. They may be branched or unbranched and soft or stiff. They may even be secretory. The trichomes help in preventing water loss due to transpiration.

6.1.2 The Ground Tissue System

All tissues except epidermis and vascular bundles constitute the **ground tissue**. It consists of simple tissues such as parenchyma, collenchyma and sclerenchyma. Parenchymatous cells are usually present in cortex, pericycle, pith and medullary rays, in the primary stems and roots. In leaves, the ground tissue consists of thin-walled chloroplast containing cells and is called **mesophyll**.

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6.1.3 The Vascular Tissue System

The vascular system consists of complex tissues, the phloem and the xylem.The xylem and phloem together constitute vascular bundles (Figure 6.2). In dicotyledonous stems, **cambium** is present between phloem and xylem. Such vascular bundles because of the presence of cambium possess the ability to form secondary xylem and phloem tissues, and hence are called **open vascular bundles**. In the monocotyledons, the vascular bundles have no cambium present in them. Hence, since they do not form secondary tissues they are referred to as **closed**. When xylem and phloem within a vascular bundle are arranged in an alternate manner along the different radii, the arrangement is called **radial** such as in roots. In **conjoint** type of vascular bundles, the xylem and phloem are jointly situated along the same radius of vascular bundles. Such vascular bundles are common in stems and leaves. The conjoint vascular bundles usually have the phloem located only on the outer side of xylem.

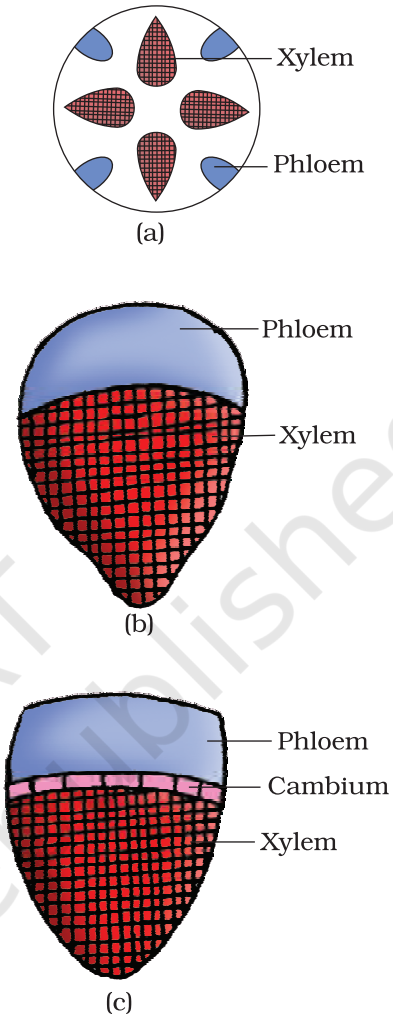

Figure 6.2 Various types of vascular bundles : (a) radial (b) conjoint closed (c) conjoint open

6.2 ANATOMY OF DICOTYLEDONOUS AND MONOCOTYLEDONOUS PLANTS

For a better understanding of tissue organisation of roots, stems and leaves, it is convenient to study the transverse sections of the mature zones of these organs.

6.2.1 Dicotyledonous Root

Look at Figure 6.3 (a), it shows the transverse section of the sunflower root. The internal tissue organisation is as follows:

The outermost layer is **epiblema.** Many of the cells of epiblema protrude in the form of unicellular root hairs. The **cortex** consists of several layers of thin-walled parenchyma cells

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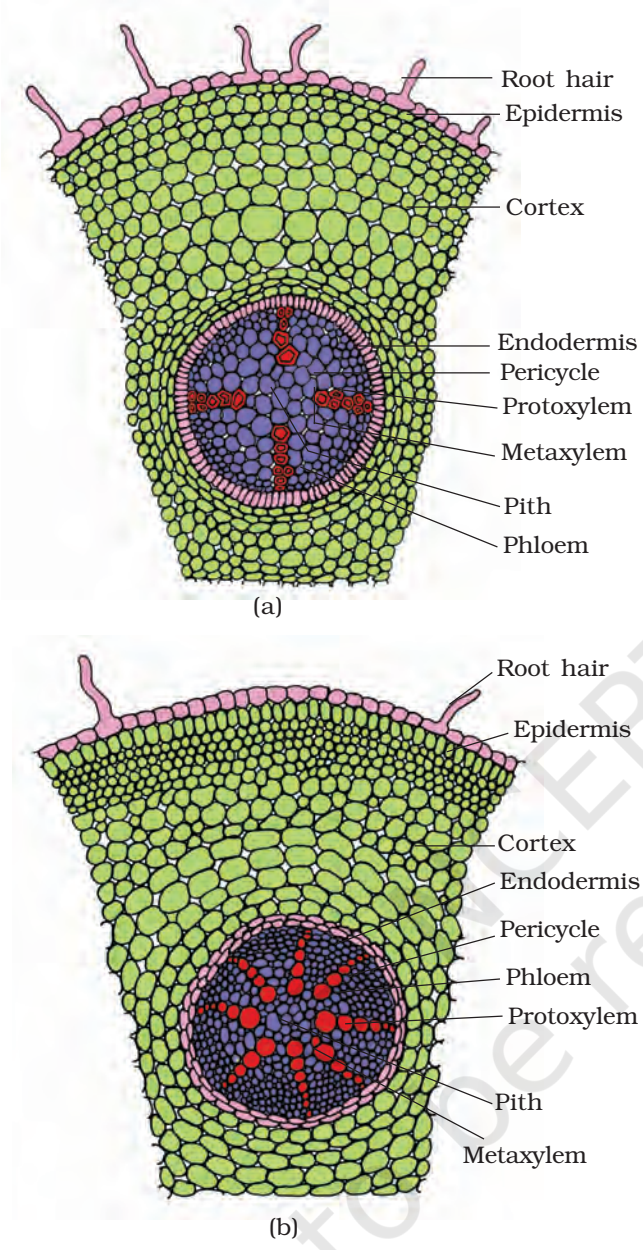

Figure 6.3 T.S. : (a) Dicot root (Primary) (b) Monocot root

with intercellular spaces. The innermost layer of the cortex is called **endodermis.** It comprises a single layer of barrel-shaped cells without any intercellular spaces. The tangential as well as radial walls of the endodermal cells have a deposition of water-impermeable, waxy material suberin in the form of **casparian strips**. Next to endodermis lies a few layers of thick-walled parenchyomatous cells referred to as **pericycle**. Initiation of lateral roots and vascular cambium during the secondary growth takes place in these cells. The pith is small or inconspicuous. The parenchymatous cells which lie between the xylem and the phloem are called **conjuctive tissue**. There are usually two to four xylem and phloem patches. Later, a cambium ring develops between the xylem and phloem. All tissues on the innerside of the endodermis such as pericycle, vascular bundles and pith constitute the **stele**.

6.2.2 Monocotyledonous Root

The anatomy of the monocot root is similar to the dicot root in many respects (Figure 6.3 b). It has epidermis, cortex, endodermis, pericycle, vascular bundles and pith. As compared to the dicot root which have fewer xylem bundles, there are usually more than six (polyarch) xylem bundles in the monocot root. Pith is large and well developed. Monocotyledonous roots do not undergo any secondary growth.

6.2.3 Dicotyledonous Stem

The transverse section of a typical young dicotyledonous stem shows that the **epidermis** is the outermost protective layer of the stem

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(Figure 6.4 a). Covered with a thin layer of cuticle, it may bear trichomes and a few stomata. The cells arranged in multiple layers between epidermis and pericycle constitute the cortex. It consists of three sub-zones. The outer **hypodermis**, consists of a few layers of collenchymatous cells just below the epidermis, which provide mechanical strength to the young stem. **Cortical layers** below hypodermis consist of rounded thin walled parenchymatous cells with conspicuous intercellular spaces. The innermost layer of the cortex is called the **endodermis.** The cells of the endodermis are rich in starch grains and the layer is also referred to as the **starch sheath. Pericycle** is

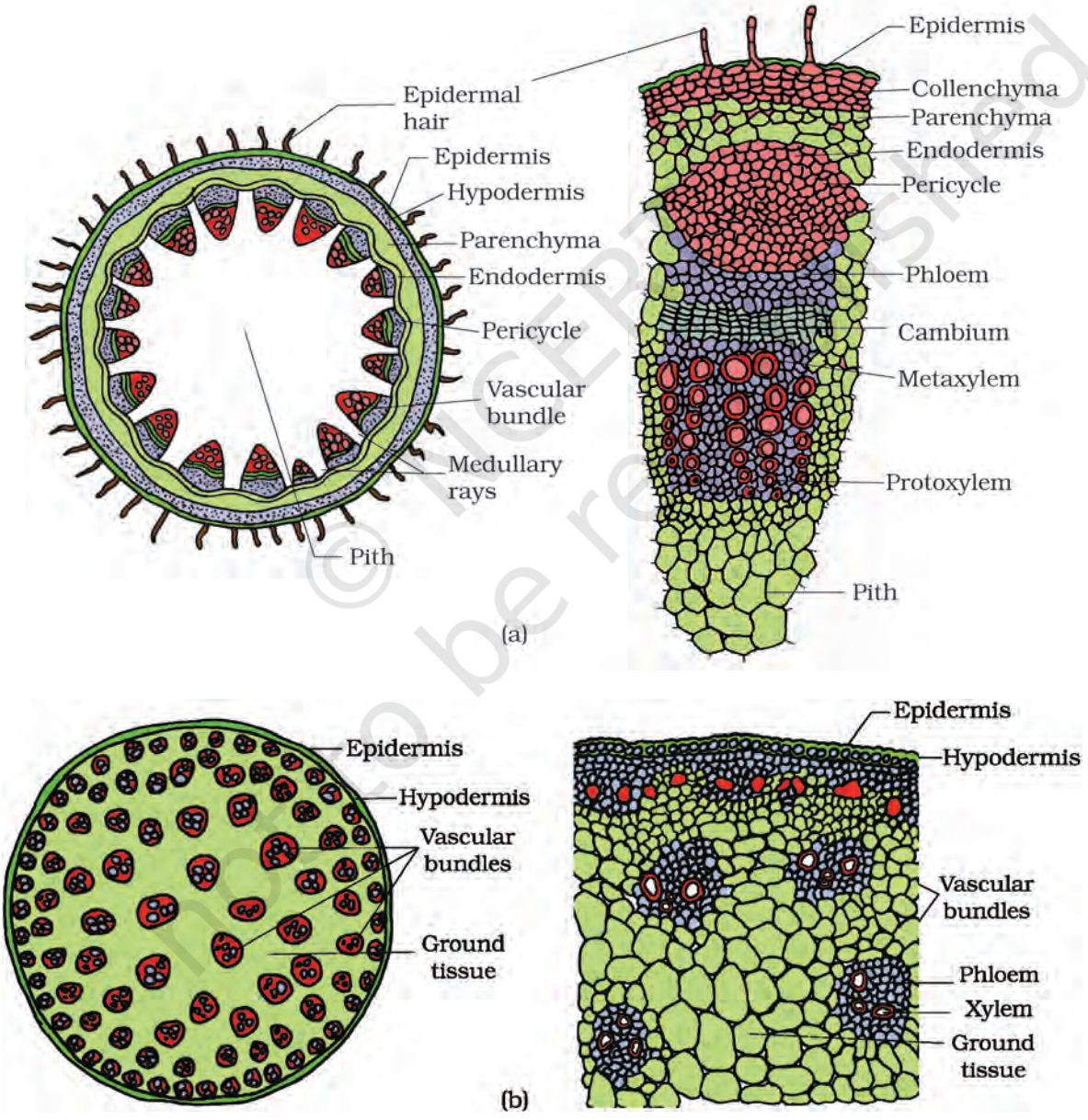

Figure 6.4 T.S. of stem : (a) Dicot (b) Monocot

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present on the inner side of the endodermis and above the phloem in the form of semi-lunar patches of sclerenchyma. In between the vascular bundles there are a few layers of radially placed parenchymatous cells, which constitute medullary rays. A large number of **vascular bundles** are arranged in a ring ; the 'ring' arrangement of vascular bundles is a characteristic of dicot stem. Each vascular bundle is conjoint, open, and with endarch protoxylem. A large number of rounded, parenchymatous cells with large intercellular spaces which occupy the central portion of the stem constitute the **pith**.

6.2.4 Monocotyledonous Stem

The monocot stem has a sclerenchymatous hypodermis, a large number of scattered vascular bundles, each surrounded by a sclerenchymatous bundle sheath, and a large, conspicuous parenchymatous ground tissue (Figure 6.4 b). Vascular bundles are conjoint and closed. Peripheral vascular bundles are generally smaller than the centrally located ones. The phloem parenchyma is absent, and water-containing cavities are present within the vascular bundles.

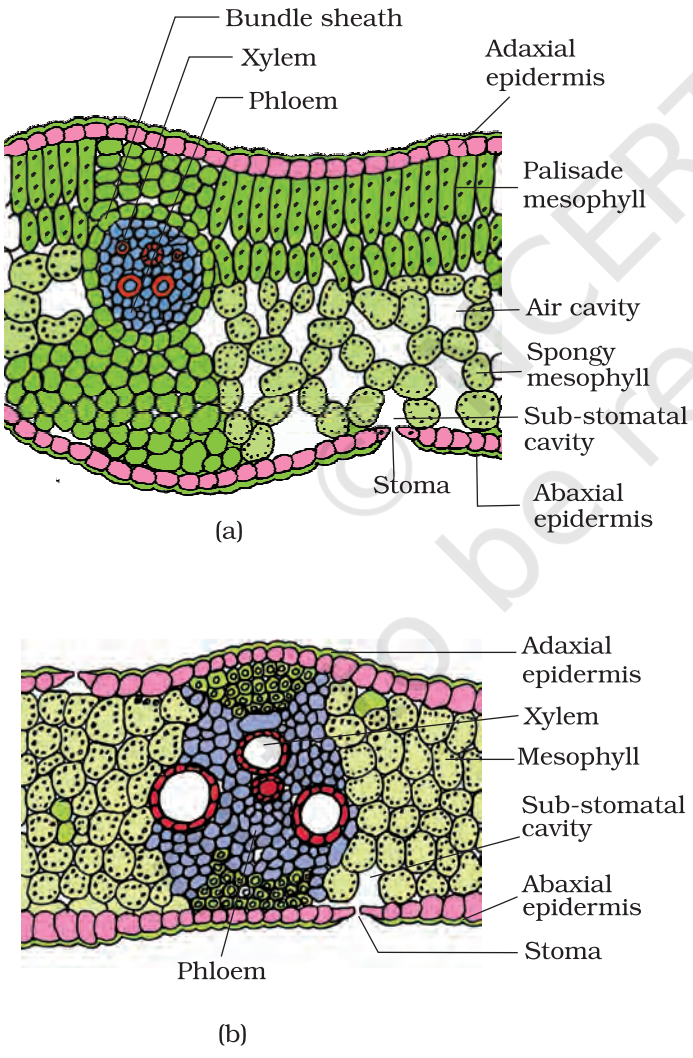

Figure 6.5 T.S. of leaf : (a) Dicot (b) Monocot

6.2.5 Dorsiventral (Dicotyledonous) Leaf

The vertical section of a dorsiventral leaf through the lamina shows three main parts, namely, epidermis, mesophyll and vascular system**.** The **epidermis** which covers both the upper surface (adaxial epidermis) and lower surface (abaxial epidermis) of the leaf has a conspicuous cuticle. The abaxial epidermis generally bears more stomata than the adaxial epidermis. The latter may even lack stomata. The tissue between the upper and the lower epidermis is called the **mesophyll**. Mesophyll, which possesses chloroplasts and carry out photosynthesis, is made up of parenchyma. It has two types of cells – the **palisade parenchyma** and the **spongy parenchyma**. The adaxially placed palisade parenchyma is made up of elongated cells, which are arranged

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vertically and parallel to each other. The oval or round and loosely arranged spongy parenchyma is situated below the palisade cells and extends to the lower epidermis. There are numerous large spaces and air cavities between these cells. **Vascular system** includes vascular bundles, which can be seen in the veins and the midrib. The size of the vascular bundles are dependent on the size of the veins. The veins vary in thickness in the reticulate venation of the dicot leaves. The vascular bundles are surrounded by a layer of thick walled **bundle sheath cells**. Look at Figure 6.5 (a) and find the position of xylem in the vascular bundle.

6.2.6 Isobilateral (Monocotyledonous) Leaf

The anatomy of isobilateral leaf is similar to that of the dorsiventral leaf in many ways. It shows the following characteristic differences. In an isobilateral leaf, the stomata are present on both the surfaces of the epidermis; and the mesophyll is not differentiated into palisade and spongy parenchyma (Figure 6.5 b).

In grasses, certain adaxial epidermal cells along the veins modify themselves into large, empty, colourless cells. These are called **bulliform cells.** When the bulliform cells in the leaves have absorbed water and are turgid, the leaf surface is exposed. When they are flaccid due to water stress, they make the leaves curl inwards to minimise water loss.

The parallel venation in monocot leaves is reflected in the near similar sizes of vascular bundles (except in main veins) as seen in vertical sections of the leaves.

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SUMMARY

Anatomically, a plant is made of different kinds of tissues. The plant tissues are broadly classified into meristematic (apical, lateral and intercalary) and permanent (simple and complex). Assimilation of food and its storage, transportation of water, minerals and photosynthates, and mechanical support are the main functions of tissues. There are three types of tissue systems – epidermal, ground and vascular. The epidermal tissue systems are made of epidermal cells, stomata and the epidermal appendages. The ground tissue system forms the main bulk of the plant. It is divided into three zones – cortex, pericycle and pith. The vascular tissue system is formed by the xylem and phloem. On the basis of presence of cambium, location of xylem and phloem, the vascular bundles are of different types. The vascular bundles form the conducting tissue and translocate water, minerals and food material.

Monocotyledonous and dicotyledonous plants show marked variation in their internal structures. They differ in type, number and location of vascular bundles. The secondary growth occurs in most of the dicotyledonous roots and stems.

EXERCISES

1. Draw illustrations to bring out the anatomical difference between
   (a) Monocot root and Dicot root
   (b) Monocot stem and Dicot stem
2. Cut a transverse section of young stem of a plant from your school garden and observe it under the microscope. How would you ascertain whether it is a monocot stem or a dicot stem? Give reasons.
3. The transverse section of a plant material shows the following anatomical features - (a) the vascular bundles are conjoint, scattered and surrounded by a sclerenchymatous bundle sheaths. (b) phloem parenchyma is absent. What will you identify it as?
4. What is stomatal apparatus? Explain the structure of stomata with a labelled diagram.
5. Name the three basic tissue systems in the flowering plants. Give the tissue names under each system.
6. How is the study of plant anatomy useful to us?
7. Describe the internal structure of a dorsiventral leaf with the help of labelled diagrams.

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Chapter 7
Structural Organisation in Animals

7.1 *Organ and Organ System*
7.2 *Frogs*

In the preceding chapters you came across a large variety of organisms, both unicellular and multicellular, of the animal kingdom. In unicellular organisms, all functions like digestion, respiration and reproduction are performed by a single cell. In the complex body of multicellular animals the same basic functions are carried out by different groups of cells in a well organised manner. The body of a simple organism like *Hydra* is made of different types of cells and the number of cells in each type can be in thousands. The human body is composed of billions of cells to perform various functions. How do these cells in the body work together? As you have already learnt in your earlier classes, in multicellular animals, a group of similar cells alongwith intercellular substances perform a specific function. Such an organisation is called **tissue**.

You may be surprised to know that all complex animals consist of only four basic types of tissues. These tissues are organised in specific proportion and pattern to form an organ like stomach, lung, heart and kidney. When two or more organs perform a common function by their physical and/or chemical interaction, they together form organ system, e.g., digestive system, respiratory system, etc. Cells, tissues, organs and organ systems split up the work in a way that exhibits division of labour and contribute to the survival of the body as a whole.

7.1 Organ and Organ System

The basic tissues as you have learnt in earlier classes, organise to form organs which in turn associate to form organ systems in the multicellular organisms. Such an organisation is essential for more efficient and better coordinated activities of millions of cells constituting an organism. Each

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organ in our body is made of one or more type of tissues. For example, our heart consists of all the four types of tissues, i.e., epithelial, connective, muscular and neural. We also notice, after some careful study that the complexity in organ and organ systems displays certain discernable trend. This discernable trend is called evolutionary trend (You will study the details in class XII). In this chapter, you are being introduced to morphology and anatomy of frog. Morphology refers to study of form or externally visible features. In the case of plants or microbes, the term morphology precisely means only this. In case of animals this refers to the external appearance of the organs or parts of the body. The word anatomy conventionally is used for the study of morphology of internal organs in the animals. You will learn the morphology and anatomy of frog representing vertebrates.

7.2 FROGS

Frogs can live both on land and in freshwater and belong to class Amphibia of phylum Chordata. The most common species of frog found in India is *Rana tigrina.*

They do not have constant body temperature i.e., their body temperature varies with the temperature of the environment. Such animals are called cold blooded or poikilotherms. You might have also noticed changes in the colour of the frogs while they are in grasses and on dry land. They have the ability to change the colour to hide them from their enemies (camouflage). This protective coloration is called mimicry. You may also know that frogs are not seen during peak summer and winter. During this period they take shelter in deep burrows to protect them from extreme heat and cold. This is known as summer sleep (aestivation) and winter sleep (hibernation) respectively.

7.2.1 Morphology

Have you ever touched the skin of frog? The skin is smooth and slippery due to the presence of mucus. The skin is always maintained in a moist condition. The colour of dorsal side of body is generally olive green with dark irregular spots. On the ventral side the skin is uniformly pale yellow. The frog never drinks water but absorb it through the skin.

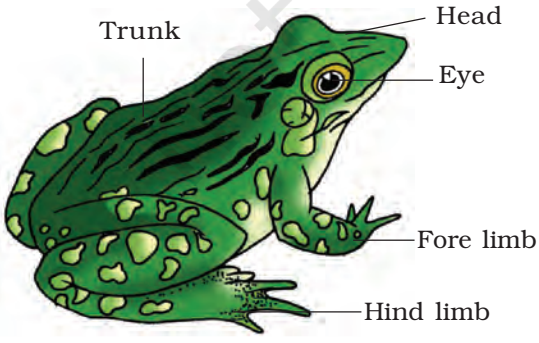

Figure 7.1 External features of frog

Body of a frog is divisible into head and trunk (Figure 7.1). A neck and tail are absent. Above the mouth, a pair of nostrils is present. Eyes are bulged and covered by a nictitating membrane that protects them while in water. On either side of eyes a membranous tympanum (ear) receives sound signals. The forelimbs and hind limbs help in

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swimming, walking, leaping and burrowing. The hind limbs end in five digits and they are larger and muscular than fore limbs that end in four digits. Feet have webbed digits that help in swimming. Frogs exhibit sexual dimorphism. Male frogs can be distinguished by the presence of sound producing vocal sacs and also a copulatory pad on the first digit of the fore limbs which are absent in female frogs.

7.2.2 Anatomy

The body cavity of frogs accommodate different organ systems such as digestive, circulatory, respiratory, nervous, excretory and reproductive systems with well developed structures and functions (Figure 7.2).

The digestive system consists of alimentary canal and digestive glands. The alimentary canal is short because frogs are carnivores and hence the length of intestine is reduced. The mouth opens into the buccal cavity that leads to the oesophagus through pharynx. Oesophagus is a short tube that opens into the stomach which in turn continues as the intestine, rectum and finally opens outside by the cloaca. Liver secretes bile that is stored in the gall bladder. Pancreas, a digestive gland produces pancreatic juice

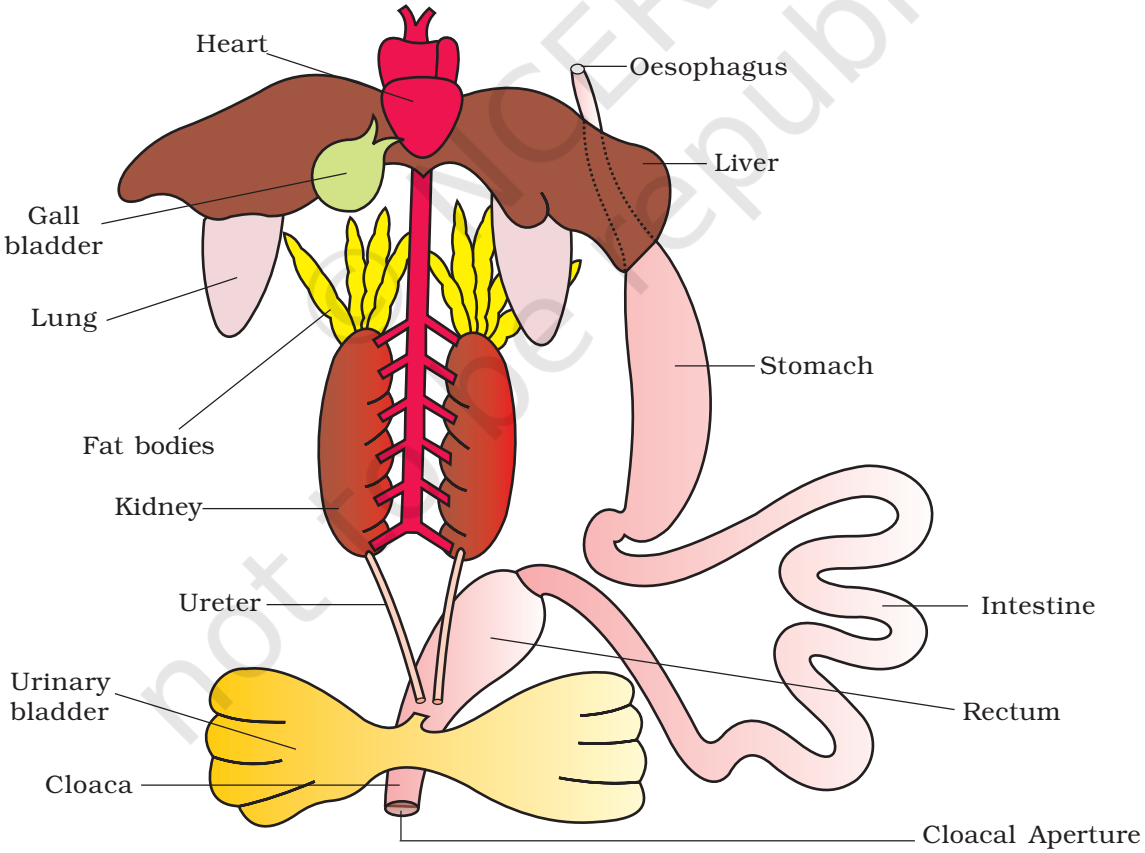

Figure 7.2 Diagrammatic representation of internal organs of frog showing complete digestive system

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containing digestive enzymes. Food is captured by the bilobed tongue. Digestion of food takes place by the action of HCl and gastric juices secreted from the walls of the stomach. Partially digested food called chyme is passed from stomach to the first part of the small intestine, the duodenum. The duodenum receives bile from gall bladder and pancreatic juices from the pancreas through a common bile duct. Bile emulsifies fat and pancreatic juices digest carbohydrates and proteins. Final digestion takes place in the intestine. Digested food is absorbed by the numerous finger-like folds in the inner wall of intestine called villi and microvilli. The undigested solid waste moves into the rectum and passes out through cloaca.

Frogs respire on land and in the water by two different methods. In water, skin acts as aquatic respiratory organ (cutaneous respiration). Dissolved oxygen in the water is exchanged through the skin by diffusion. On land, the buccal cavity, skin and lungs act as the respiratory organs. The respiration by lungs is called pulmonary respiration. The lungs are a pair of elongated, pink coloured sac-like structures present in the upper part of the trunk region (thorax). Air enters through the nostrils into the buccal cavity and then to lungs. During aestivation and hibernation gaseous exchange takes place through skin.

The vascular system of frog is well-developed closed type. Frogs have a lymphatic system also. The blood vascular system involves heart, blood vessels and blood. The lymphatic system consists of lymph, lymph channels and lymph nodes. Heart is a muscular structure situated in the upper part of the body cavity. It has three chambers, two atria and one ventricle and is covered by a membrane called pericardium. A triangular structure called sinus venosus joins the right atrium. It receives blood through the major veins called vena cava. The ventricle opens into a sac-like conus arteriosus on the ventral side of the heart. The blood from the heart is carried to all parts of the body by the arteries (arterial system). The veins collect blood from different parts of body to the heart and form the venous system. Special venous connection between liver and intestine as well as the kidney and lower parts of the body are present in frogs. The former is called hepatic portal system and the latter is called renal portal system. The blood is composed of plasma and cells. The blood cells are RBC (red blood cells) or erythrocytes, WBC (white blood cells) or leucocytes and platelets. RBC's are nucleated and contain red coloured pigment namely haemoglobin. The lymph is different from blood. It lacks few proteins and RBCs. The blood carries nutrients, gases and water to the respective sites during the circulation. The circulation of blood is achieved by the pumping action of the muscular heart.

The elimination of nitrogenous wastes is carried out by a well developed excretory system. The excretory system consists of a pair of kidneys, ureters, cloaca and urinary bladder. These are compact, dark red and bean like structures situated a little posteriorly in the body cavity on both sides of vertebral column. Each kidney is composed of several structural and functional units called uriniferous tubules or nephrons. Two ureters emerge from the kidneys in the male frogs. The ureters act as urinogenital duct which opens into the cloaca. In females the ureters and

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oviduct open seperately in the cloaca. The thin-walled urinary bladder is present ventral to the rectum which also opens in the cloaca. The frog excretes urea and thus is a **ureotelic** animal. Excretory wastes are carried by blood into the kidney where it is separated and excreted.

The system for control and coordination is highly evolved in the frog. It includes both neural system and endocrine glands. The chemical coordination of various organs of the body is achieved by hormones which are secreted by the endocrine glands. The prominent endocrine glands found in frog are pituitary, thyroid, parathyroid, thymus, pineal body, pancreatic islets, adrenals and gonads. The nervous system is organised into a central nervous system (brain and spinal cord), a peripheral nervous system (cranial and spinal nerves) and an autonomic nervous system (sympathetic and parasympathetic). There are ten pairs of cranial nerves arising from the brain. Brain is enclosed in a bony structure called brain box (cranium). The brain is divided into fore-brain, mid-brain and hind-brain. Forebrain includes olfactory lobes, paired cerebral hemispheres and unpaired diencephalon. The midbrain is characterised by a pair of optic lobes. Hind-brain consists of cerebellum and medulla oblongata. The medulla oblongata passes out through the foramen magnum and continues into spinal cord, which is enclosed in the vertebral column.

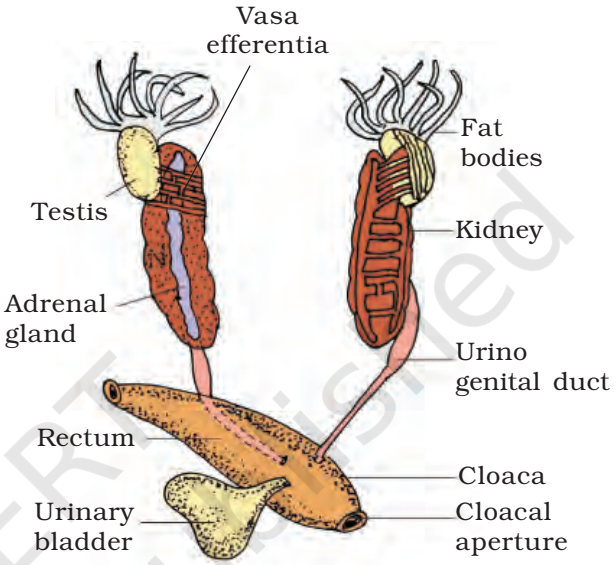

Figure 7.3 Male reproductive system

Frog has different types of sense organs, namely organs of touch (sensory papillae), taste (taste buds), smell (nasal epithelium), vision (eyes) and hearing (tympanum with internal ears). Out of these, eyes and internal ears are well-organised structures and the rest are cellular aggregations around nerve endings. Eyes in a frog are a pair of spherical structures situated in the orbit in skull. These are simple eyes (possessing only one unit). External ear is absent in frogs and only tympanum can be seen externally. The ear is an organ of hearing as well as balancing (equilibrium).

Frogs have well organised male and female reproductive systems. Male reproductive organs consist of a pair of yellowish ovoid testes (Figure 7.3), which are found adhered to the upper part of kidneys by a double fold of peritoneum called mesorchium. Vasa efferentia are 10-12 in number that arise from testes. They enter the kidneys on their side and open into Bidder's

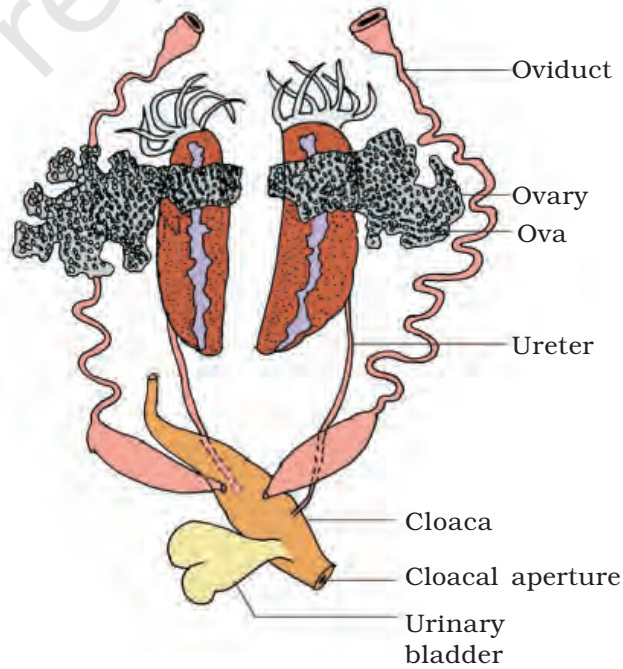

Figure 7.4 Female reproductive system

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canal. Finally it communicates with the urinogenital duct that comes out of the kidneys and opens into the cloaca. The cloaca is a small, median chamber that is used to pass faecal matter, urine and sperms to the exterior.

The female reproductive organs include a pair of ovaries (Figure 7.4). The ovaries are situated near kidneys and there is no functional connection with kidneys. A pair of oviduct arising from the ovaries opens into the cloaca separately. A mature female can lay 2500 to 3000 ova at a time. Fertilisation is external and takes place in water. Development involves a larval stage called tadpole. Tadpole undergoes metamorphosis to form the adult.

Frogs are beneficial for mankind because they eat insects and protect the crop. Frogs maintain ecological balance because these serve as an important link of food chain and food web in the ecosystem. In some countries the muscular legs of frog are used as food by man.

SUMMARY

Cells, tissues, organs and organ systems split up the work in a way that ensures the survival of the body as a whole and exhibit division of labour. A tissue is defined as group of cells along with intercellular substances performing one or more functions in the body. Epithelia are sheet like tissues lining the body's surface and its cavities, ducts and tubes. Epithelia have one free surface facing a body fluid or the outside environment. Their cells are structurally and functionally connected at junctions.

The Indian bullfrog, *Rana tigrina,* is the common frog found in India. Body is covered by skin. Mucous glands are present in the skin which is highly vascularised and helps in respiration in water and on land. Body is divisible into head and trunk. A muscular tongue is present, which is bilobed at the tip and is used in capturing the prey. The alimentary canal consists of oesophagous, stomach, intestine and rectum, which open into the cloaca. The main digestive glands are liver and pancreas. It can respire in water through skin and through lungs on land. Circulatory system is closed with single circulation. RBCs are nucleated. Nervous system is organised into central, peripheral and autonomic. The organs of urinogenital system are kidneys and urinogenital ducts, which open into the cloaca. The male reproductive organ is a pair of testes. The female reproductive organ is a pair of ovaries. A female lays 2500-3000 ova at a time. The fertilisation and development are external. The eggs hatch into tadpoles, which metamorphose into frogs.

EXERCISES

1. Draw a neat diagram of digestive system of frog.
2. Mention the function of the Ureters in frog.

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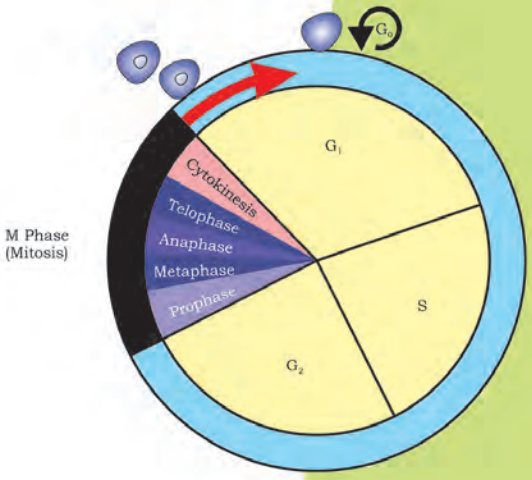

UNIT 3

CELL: STRUCTURE AND FUNCTIONS

Chapter 8
Cell: The Unit of Life

Chapter 9
Biomolecules

Chapter 10
Cell Cycle and
Cell Division

Biology is the study of living organisms. The detailed description of their form and appearance only brought out their diversity. It is the cell theory that emphasised the unity underlying this diversity of forms, i.e., the cellular organisation of all life forms. A description of cell structure and cell growth by division is given in the chapters comprising this unit. Cell theory also created a sense of mystery around living phenomena, i.e., physiological and behavioural processes. This mystery was the requirement of integrity of cellular organisation for living phenomena to be demonstrated or observed. In studying and understanding the physiological and behavioural processes, one can take a physico-chemical approach and use cell-free systems to investigate. This approach enables us to describe the various processes in molecular terms. The approach is established by analysis of living tissues for elements and compounds. It will tell us what types of organic compounds are present in living organisms. In the next stage, one can ask the question: What are these compounds doing inside a cell? And, in what way they carry out gross physiological processes like digestion, excretion, memory, defense, recognition, etc. In other words we answer the question, what is the molecular basis of all physiological processes? It can also explain the abnormal processes that occur during any diseased condition. This physico-chemical approach to study and understand living organisms is called 'Reductionist Biology'. The concepts and techniques of physics and chemistry are applied to understand biology. In Chapter 9 of this unit, a brief description of biomolecules is provided.

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G.N. Ramachandran
(1922 – 2001)

G.N. RAMACHANDRAN, an outstanding figure in the field of protein structure, was the founder of the 'Madras school' of conformational analysis of biopolymers. His discovery of the triple helical structure of collagen published in *Nature* in 1954 and his analysis of the allowed conformations of proteins through the use of the 'Ramachandran plot' rank among the most outstanding contributions in structural biology. He was born on October 8, 1922, in a small town, not far from Cochin on the southwestern coast of India. His father was a professor of mathematics at a local college and thus had considerable influence in shaping Ramachandran's interest in mathematics. After completing his school years, Ramachandran graduated in 1942 as the top-ranking student in the B.Sc. (Honors) Physics course of the University of Madras. He received a Ph.D. from Cambridge University in 1949. While at Cambridge, Ramachandran met Linus Pauling and was deeply influenced by his publications on models of the α-helix and β-sheet structures that directed his attention to solving the structure of collagen. He passed away at the age of 78, on April 7, 2001.

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Chapter 8
Cell: The Unit of Life

8.1 *What is a Cell?*
8.2 *Cell Theory*
8.3 *An Overview of Cell*
8.4 *Prokaryotic Cells*
8.5 *Eukaryotic Cells*

When you look around, you see both living and non-living things. You must have wondered and asked yourself – 'what is it that makes an organism living, or what is it that an inanimate thing does not have which a living thing has' ? The answer to this is the presence of the basic unit of life – the cell in all living organisms.

All organisms are composed of cells. Some are composed of a single cell and are called unicellular organisms while others, like us, composed of many cells, are called multicellular organisms.

8.1 What is a Cell?

Unicellular organisms are capable of (i) independent existence and (ii) performing the essential functions of life. Anything less than a complete structure of a cell does not ensure independent living. Hence, cell is the fundamental structural and functional unit of all living organisms.

Antonie Von Leeuwenhoek first saw and described a live cell. Robert Brown later discovered the nucleus. The invention of the microscope and its improvement leading to the electron microscope revealed all the structural details of the cell.

8.2 Cell Theory

In 1838, Matthias Schleiden, a German botanist, examined a large number of plants and observed that all plants are composed of different kinds of cells which form the tissues of the plant. At about the same time, Theodore

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Schwann (1839), a German Zoologist, studied different types of animal cells and reported that cells had a thin outer layer which is today known as the 'plasma membrane'. He also concluded, based on his studies on plant tissues, that the presence of cell wall is a unique character of the plant cells. On the basis of this, Schwann proposed the hypothesis that the bodies of animals and plants are composed of cells and products of cells.

Schleiden and Schwann together formulated the cell theory. This theory however, did not explain as to how new cells were formed. Rudolf Virchow (1855) first explained that cells divided and new cells are formed from pre-existing cells (*Omnis cellula-e cellula*). He modified the hypothesis of Schleiden and Schwann to give the cell theory a final shape. Cell theory as understood today is:

(i) all living organisms are composed of cells and products of cells.

(ii) all cells arise from pre-existing cells.

8.3 AN OVERVIEW OF CELL

You have earlier observed cells in an onion peel and/or human cheek cells under the microscope. Let us recollect their structure. The onion cell which is a typical plant cell, has a distinct cell wall as its outer boundary and just within it is the cell membrane. The cells of the human cheek have an outer membrane as the delimiting structure of the cell. Inside each cell is a dense membrane bound structure called nucleus. This nucleus contains the chromosomes which in turn contain the genetic material, DNA. Cells that have membrane bound nuclei are called eukaryotic whereas cells that lack a membrane bound nucleus are prokaryotic. In both prokaryotic and eukaryotic cells, a semi-fluid matrix called cytoplasm occupies the volume of the cell. The cytoplasm is the main arena of cellular activities in both the plant and animal cells. Various chemical reactions occur in it to keep the cell in the 'living state'.

Besides the nucleus, the eukaryotic cells have other membrane bound distinct structures called **organelles** like the endoplasmic reticulum (ER), the golgi complex, lysosomes, mitochondria, microbodies and vacuoles. The prokaryotic cells lack such membrane bound organelles.

Ribosomes are non-membrane bound organelles found in all cells – both eukaryotic as well as prokaryotic. Within the cell, ribosomes are found not only in the cytoplasm but also within the two organelles – chloroplasts (in plants) and mitochondria and on rough ER.

Animal cells contain another non-membrane bound organelle called centrosome which helps in cell division.

Cells differ greatly in size, shape and activities (Figure 8.1). For example, Mycoplasmas, the smallest cells, are only 0.3 μm in length while bacteria

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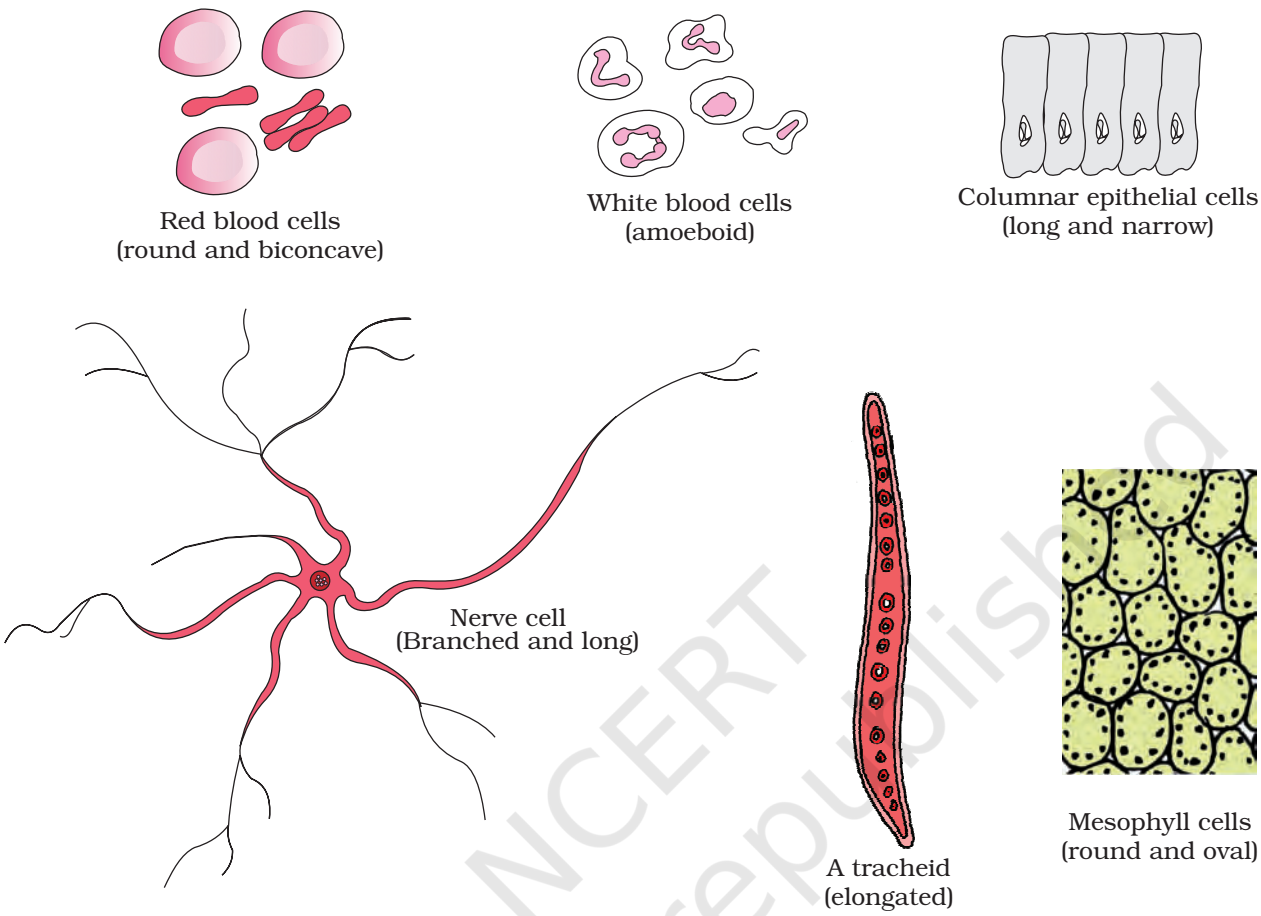

Figure 8.1 Diagram showing different shapes of the cells

could be 3 to 5 µm. The largest isolated single cell is the egg of an ostrich. Among multicellular organisms, human red blood cells are about 7.0 µm in diameter. Nerve cells are some of the longest cells. Cells also vary greatly in their shape. They may be disc-like, polygonal, columnar, cuboid, thread like, or even irregular. The shape of the cell may vary with the function they perform.

8.4 PROKARYOTIC CELLS

The prokaryotic cells are represented by bacteria, blue-green algae, mycoplasma and PPLO (Pleuro Pneumonia Like Organisms). They are generally smaller and multiply more rapidly than the eukaryotic cells (Figure 8.2). They may vary greatly in shape and size. The four basic shapes of bacteria are bacillus (rod like), coccus (spherical), vibrio (comma shaped) and spirillum (spiral).

The organisation of the prokaryotic cell is fundamentally similar even though prokaryotes exhibit a wide variety of shapes and functions. All

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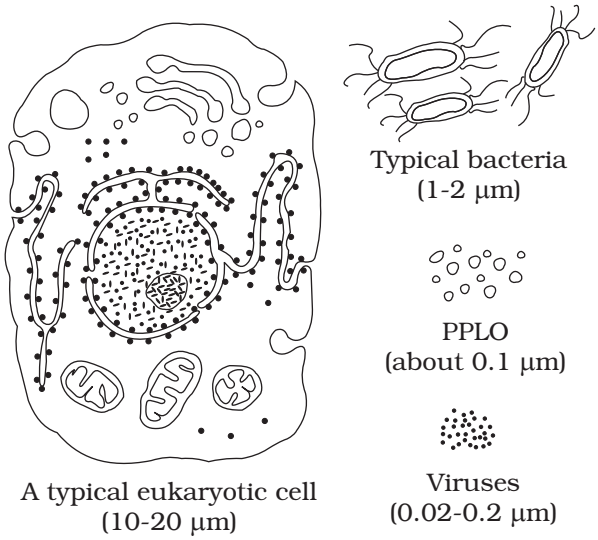

Figure 8.2 Diagram showing comparison of eukaryotic cell with other organisms

prokaryotes have a cell wall surrounding the cell membrane except in mycoplasma. The semi-fluid matrix filling the cell is the cytoplasm. There is no well-defined nucleus. The genetic material is basically naked, not enveloped by a nuclear membrane. In addition to the genomic DNA (the single chromosome/circular DNA), many bacteria have small circular DNA outside the genomic DNA. These smaller DNA are called plasmids. The plasmid DNA confers certain unique phenotypic characters to such bacteria. One such character is resistance to antibiotics. In higher classes you will learn that this plasmid DNA is used to monitor bacterial transformation with foreign DNA. Nuclear membrane is found in eukaryotes. No organelles, like the ones in eukaryotes, are found in prokaryotic cells except for ribosomes. Prokaryotes have something unique in the form of inclusions. A specialised differentiated form of cell membrane called mesosome is the characteristic of prokaryotes. They are essentially infoldings of cell membrane.

8.4.1 Cell Envelope and its Modifications

Most prokaryotic cells, particularly the bacterial cells, have a chemically complex cell envelope. The cell envelope consists of a tightly bound three layered structure i.e., the outermost glycocalyx followed by the cell wall and then the plasma membrane. Although each layer of the envelope performs distinct function, they act together as a single protective unit. Bacteria can be classified into two groups on the basis of the differences in the cell envelopes and the manner in which they respond to the staining procedure developed by Gram viz., those that take up the gram stain are **Gram positive** and the others that do not are called **Gram negative** bacteria.

Glycocalyx differs in composition and thickness among different bacteria. It could be a loose sheath called the **slime layer** in some, while in others it may be thick and tough, called the **capsule**. The **cell wall** determines the shape of the cell and provides a strong structural support to prevent the bacterium from bursting or collapsing.

The plasma membrane is selectively permeable in nature and interacts with the outside world. This membrane is similar structurally to that of the eukaryotes.

A special membranous structure is the **mesosome** which is formed by the extensions of plasma membrane into the cell. These extensions are in the **form of vesicles, tubules and lamellae**. They help in cell wall

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formation, DNA replication and distribution to daughter cells. They also help in respiration, secretion processes, to increase the surface area of the plasma membrane and enzymatic content. In some prokaryotes like cyanobacteria, there are other membranous extensions into the cytoplasm called chromatophores which contain pigments.

Bacterial cells may be motile or non-motile. If motile, they have thin filamentous extensions from their cell wall called flagella. Bacteria show a range in the number and arrangement of flagella. Bacterial flagellum is composed of three parts – **filament, hook** and **basal body**. The filament is the longest portion and extends from the cell surface to the outside.

Besides flagella, Pili and Fimbriae are also surface structures of the bacteria but do not play a role in motility. The **pili** are elongated tubular structures made of a special protein. The **fimbriae** are small bristle like fibres sprouting out of the cell. In some bacteria, they are known to help attach the bacteria to rocks in streams and also to the host tissues.

8.4.2 Ribosomes and Inclusion Bodies

In prokaryotes, ribosomes are associated with the plasma membrane of the cell. They are about 15 nm by 20 nm in size and are made of two subunits - 50S and 30S units which when present together form 70S prokaryotic ribosomes. Ribosomes are the site of protein synthesis. Several ribosomes may attach to a single mRNA and form a chain called **polyribosomes** or **polysome**. The ribosomes of a polysome translate the mRNA into proteins.

Inclusion bodies: Reserve material in prokaryotic cells are stored in the cytoplasm in the form of inclusion bodies. These are not bound by any membrane system and lie free in the cytoplasm, e.g., phosphate granules, cyanophycean granules and glycogen granules. Gas vacuoles are found in blue green and purple and green photosynthetic bacteria.

8.5 EUKARYOTIC CELLS

The eukaryotes include all the protists, plants, animals and fungi. In eukaryotic cells there is an extensive compartmentalisation of cytoplasm through the presence of membrane bound organelles. Eukaryotic cells possess an organised nucleus with a nuclear envelope. In addition, eukaryotic cells have a variety of complex locomotory and cytoskeletal structures. Their genetic material is organised into chromosomes.

All eukaryotic cells are not identical. Plant and animal cells are different as the former possess cell walls, plastids and a large central vacuole which are absent in animal cells. On the other hand, animal cells have centrioles which are absent in almost all plant cells (Figure 8.3).

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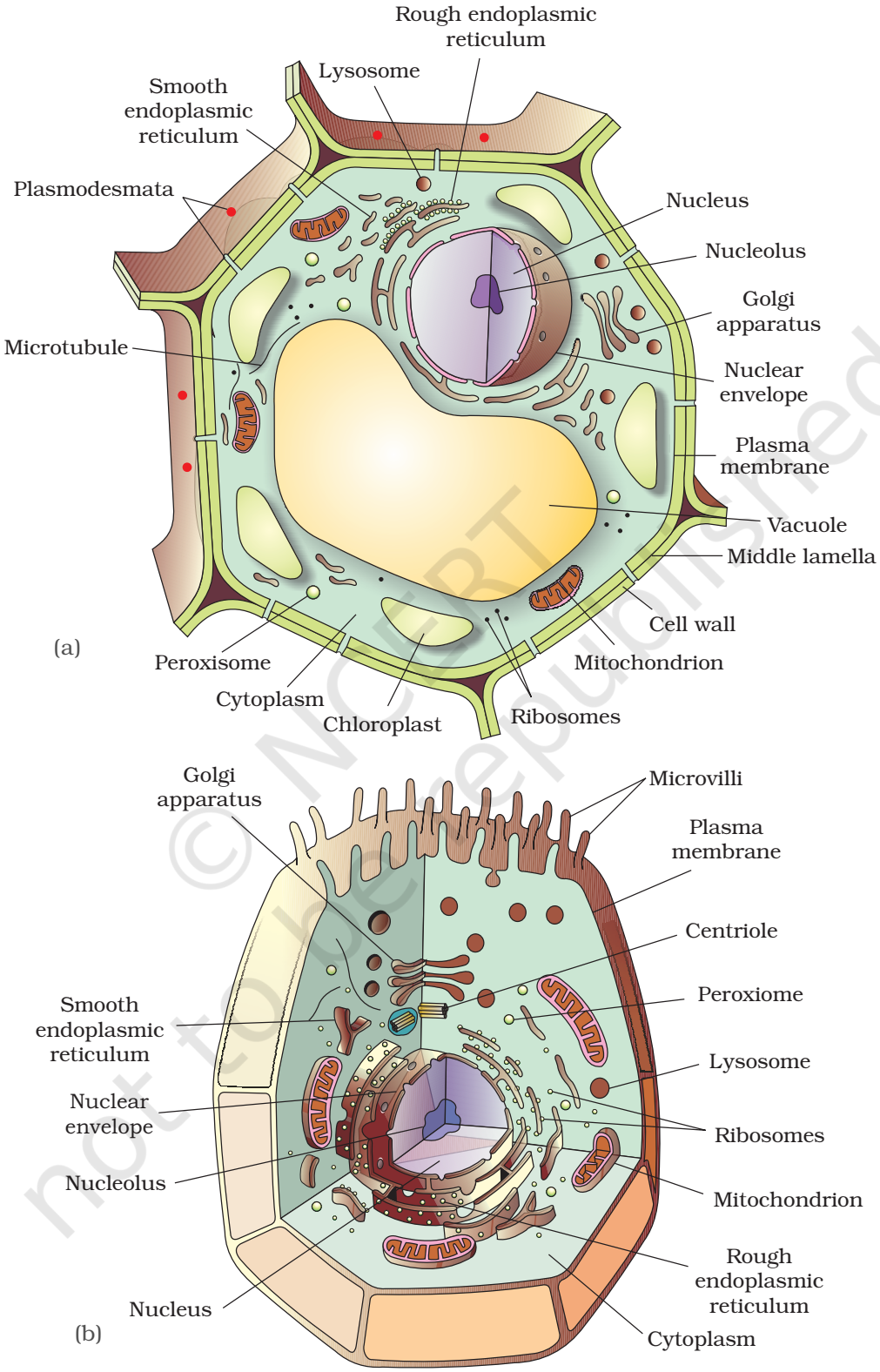

Figure 8.3 Diagram showing : (a) Plant cell (b) Animal cell

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Let us now look at individual cell organelles to understand their structure and functions.

8.5.1 Cell Membrane

The detailed structure of the membrane was studied only after the advent of the electron microscope in the 1950s. Meanwhile, chemical studies on the cell membrane, especially in human red blood cells (RBCs), enabled the scientists to deduce the possible structure of plasma membrane.

These studies showed that the cell membrane is mainly composed of lipids and proteins. The major lipids are phospholipids that are arranged in a bilayer. Also, the lipids are arranged within the membrane with the polar head towards the outer sides and the hydrophobic tails towards the inner part.This ensures that the nonpolar tail of saturated hydrocarbons is protected from the aqueous environment (Figure 8.4). In addition to phospholipids, membrane also contains cholesterol.

Later, biochemical investigation clearly revealed that the cell membranes also possess protein and carbohydrate. The ratio of protein and lipid varies considerably in different cell types. In human beings, the membrane of the erythrocyte has approximately 52 per cent protein and 40 per cent lipids.

Depending on the ease of extraction, membrane proteins can be classified as integral and peripheral. Peripheral proteins lie on the surface of membrane while the integral proteins are partially or totally buried in the membrane.

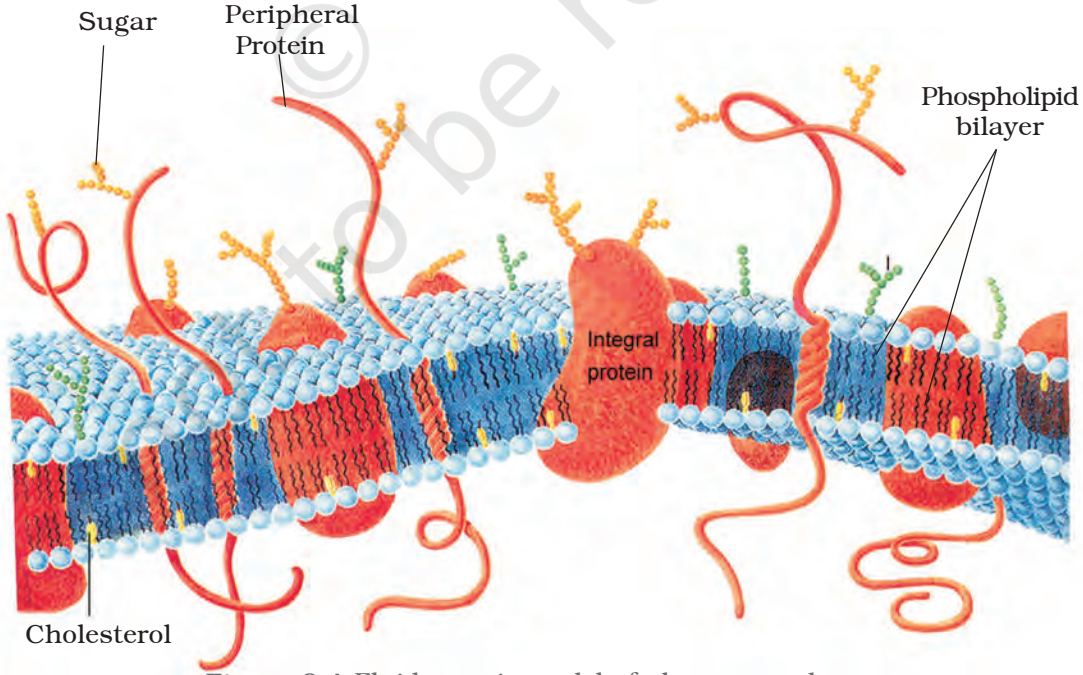

Figure 8.4 Fluid mosaic model of plasma membrane

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An improved model of the structure of cell membrane was proposed by Singer and Nicolson (1972) widely accepted as **fluid mosaic model** (Figure 8.4). According to this, the quasi-fluid nature of lipid enables lateral movement of proteins within the overall bilayer. This ability to move within the membrane is measured as its fluidity.

The fluid nature of the membrane is also important from the point of view of functions like cell growth, formation of intercellular junctions, secretion, endocytosis, cell division etc.

One of the most important functions of the plasma membrane is the transport of the molecules across it. The membrane is selectively permeable to some molecules present on either side of it. Many molecules can move briefly across the membrane without any requirement of energy and this is called the **passive transport**. Neutral solutes may move across the membrane by the process of simple diffusion along the concentration gradient, i.e., from higher concentration to the lower. Water may also move across this membrane from higher to lower concentration. Movement of water by diffusion is called **osmosis**. As the polar molecules cannot pass through the nonpolar lipid bilayer, they require a carrier protein of the membrane to facilitate their transport across the membrane. A few ions or molecules are transported across the membrane against their concentration gradient, i.e., from lower to the higher concentration. Such a transport is an energy dependent process, in which ATP is utilised and is called **active transport**, e.g., Na^+/K^+ Pump.

8.5.2 Cell Wall

As you may recall, a non-living rigid structure called the cell wall forms an outer covering for the plasma membrane of fungi and plants. Cell wall not only gives shape to the cell and protects the cell from mechanical damage and infection, it also helps in cell-to-cell interaction and provides barrier to undesirable macromolecules. Algae have cell wall, made of cellulose, galactans, mannans and minerals like calcium carbonate, while in other plants it consists of cellulose, hemicellulose, pectins and proteins. The cell wall of a young plant cell, the **primary wall** is capable of growth, which gradually diminishes as the cell matures and the secondary wall is formed on the inner (towards membrane) side of the cell.

The middle lamella is a layer mainly of calcium pectate which holds or glues the different neighbouring cells together. The cell wall and middle lamellae may be traversed by plasmodesmata which connect the cytoplasm of neighbouring cells.

8.5.3 Endomembrane System

While each of the membranous organelles is distinct in terms of its

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structure and function, many of these are considered together as an endomembrane system because their functions are coordinated. The endomembrane system include endoplasmic reticulum (ER), golgi complex, lysosomes and vacuoles. Since the functions of the mitochondria, chloroplast and peroxisomes are not coordinated with the above components, these are not considered as part of the endomembrane system.

8.5.3.1 *The Endoplasmic Reticulum (ER)*

Electron microscopic studies of eukaryotic cells reveal the presence of a network or reticulum of tiny tubular structures scattered in the cytoplasm that is called the endoplasmic reticulum (ER) (Figure 8.5). Hence, ER divides the intracellular space into two distinct compartments, i.e., luminal (inside ER) and extra luminal (cytoplasm) compartments.

The ER often shows ribosomes attached to their outer surface. The endoplasmic reticulun bearing ribosomes on their surface is called rough endoplasmic reticulum (RER). In the absence of ribosomes they appear smooth and are called smooth endoplasmic reticulum (SER).

RER is frequently observed in the cells actively involved in protein synthesis and secretion. They are extensive and continuous with the outer membrane of the nucleus.

The smooth endoplasmic reticulum is the major site for synthesis of lipid. In animal cells lipid-like steroidal hormones are synthesised in SER.

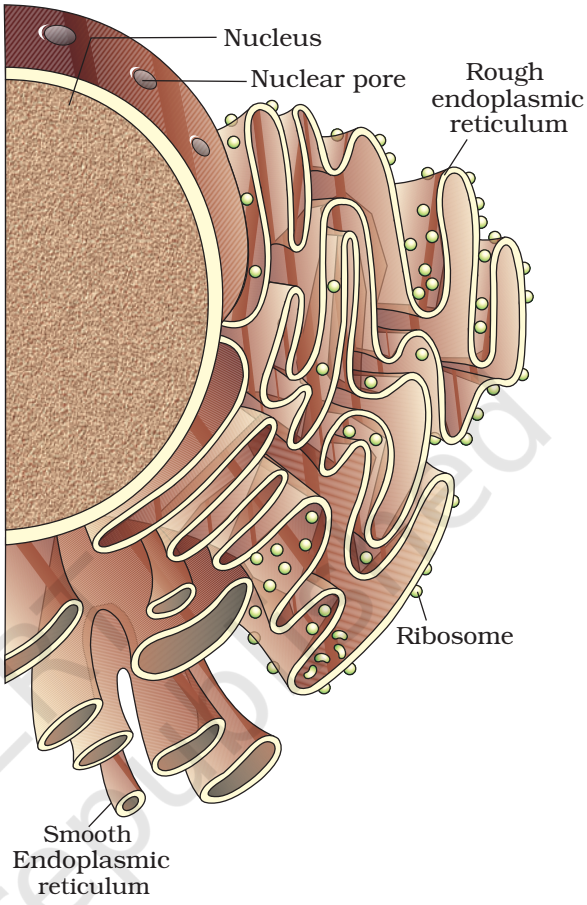

Figure 8.5 Endoplasmic reticulum

8.5.3.2 *Golgi apparatus*

Camillo Golgi (1898) first observed densely stained reticular structures near the nucleus. These were later named Golgi bodies after him. They consist of many flat, disc-shaped sacs or cisternae of 0.5µm to 1.0µm diameter (Figure 8.6). These are stacked parallel to each other. Varied number of cisternae are present in a Golgi complex. The Golgi cisternae are concentrically arranged near the nucleus with distinct convex *cis* or the forming

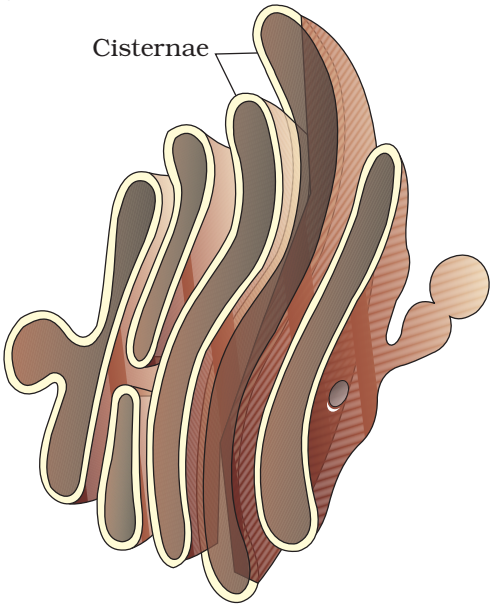

Figure 8.6 Golgi apparatus

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face and concave *trans* or the maturing face. The *cis* and the *trans* faces of the organelle are entirely different, but interconnected.

The golgi apparatus principally performs the function of packaging materials, to be delivered either to the intra-cellular targets or secreted outside the cell. Materials to be packaged in the form of vesicles from the ER fuse with the *cis* face of the golgi apparatus and move towards the maturing face. This explains, why the golgi apparatus remains in close association with the endoplasmic reticulum. A number of proteins synthesised by ribosomes on the endoplasmic reticulum are modified in the cisternae of the golgi apparatus before they are released from its *trans* face. Golgi apparatus is the important site of formation of glycoproteins and glycolipids.

8.5.3.3 Lysosomes

These are membrane bound vesicular structures formed by the process of packaging in the golgi apparatus. The isolated lysosomal vesicles have been found to be very rich in almost all types of hydrolytic enzymes (hydrolases – lipases, proteases, carbohydrases) optimally active at the acidic pH. These enzymes are capable of digesting carbohydrates, proteins, lipids and nucleic acids.

8.5.3.4 Vacuoles

The vacuole is the membrane-bound space found in the cytoplasm. It contains water, sap, excretory product and other materials not useful for the cell. The vacuole is bound by a single membrane called tonoplast. In plant cells the vacuoles can occupy up to 90 per cent of the volume of the cell.

In plants, the tonoplast facilitates the transport of a number of ions and other materials against concentration gradients into the vacuole, hence their concentration is significantly higher in the vacuole than in the cytoplasm.

In *Amoeba,* the **contractile vacuole** is important for osmoregulation and excretion. In many cells, as in protists, **food vacuoles** are formed by engulfing the food particles.

8.5.4 Mitochondria

Mitochondria (sing.: mitochondrion), unless specifically stained, are not easily visible under the microscope. The number of mitochondria per cell is variable depending on the physiological activity of the cells. In terms of shape and size also, considerable degree of variability is observed. Typically it is sausage-shaped or cylindrical having a diameter of 0.2-1.0μm (average 0.5μm) and length 1.0-4.1μm. Each mitochondrion is a double

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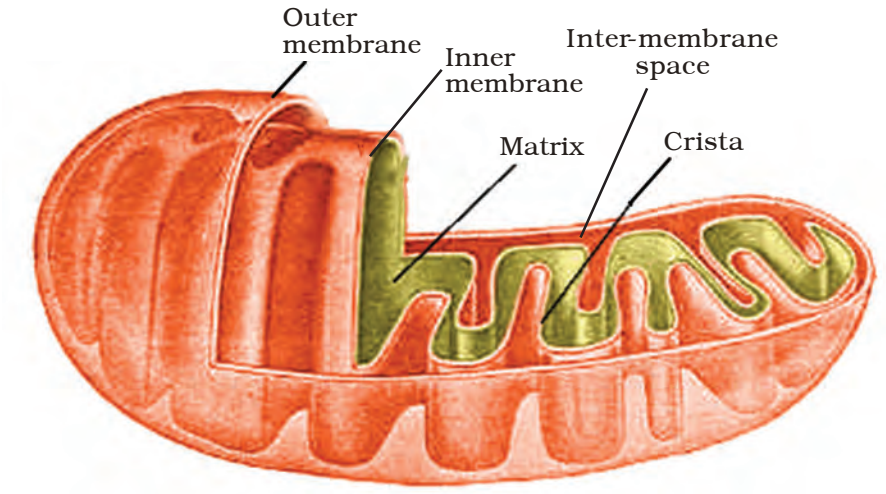

Figure 8.7 Structure of mitochondrion (Longitudinal section)

membrane-bound structure with the outer membrane and the inner membrane dividing its lumen distinctly into two aqueous compartments, i.e., the outer compartment and the inner compartment. The inner compartment is filled with a dense homogeneous substance called the **matrix**. The outer membrane forms the continuous limiting boundary of the organelle. The inner membrane forms a number of infoldings called the cristae (sing.: crista) towards the matrix (Figure 8.7). The cristae increase the surface area. The two membranes have their own specific enzymes associated with the mitochondrial function. Mitochondria are the sites of aerobic respiration. They produce cellular energy in the form of ATP, hence they are called 'power houses' of the cell. The matrix also possesses single circular DNA molecule, a few RNA molecules, ribosomes (70S) and the components required for the synthesis of proteins. The mitochondria divide by fission.

8.5.5 Plastids

Plastids are found in all plant cells and in euglenoides. These are easily observed under the microscope as they are large. They bear some specific pigments, thus imparting specific colours to the plants. Based on the type of pigments plastids can be classified into **chloroplasts, chromoplasts** and **leucoplasts.**

The chloroplasts contain **chlorophyll** and carotenoid pigments which are responsible for trapping light energy essential for photosynthesis. In the chromoplasts, fat soluble **carotenoid** pigments like carotene, xanthophylls and others are present. This gives the part of the plant a yellow, orange or red colour. The leucoplasts are the colourless plastids of varied shapes and sizes with stored nutrients: **Amyloplasts** store carbohydrates (starch), e.g., potato; **elaioplasts** store oils and fats whereas

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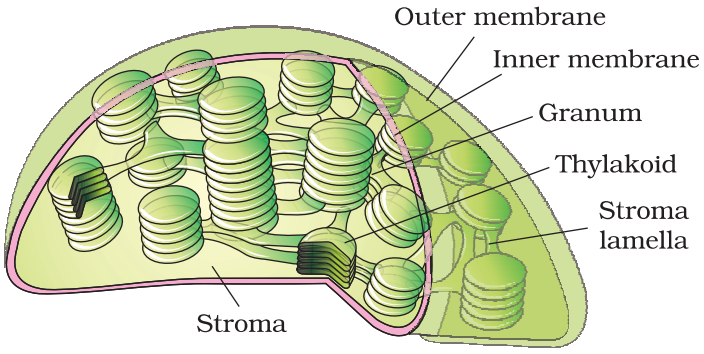

Figure 8.8 Sectional view of chloroplast

the **aleuroplasts** store proteins.

Majority of the chloroplasts of the green plants are found in the mesophyll cells of the leaves. These are lens-shaped, oval, spherical, discoid or even ribbon-like organelles having variable length (5-10µm) and width (2-4µm). Their number varies from 1 per cell of the *Chlamydomonas*, a green alga to 20-40 per cell in the mesophyll.

Like mitochondria, the chloroplasts are also double membrane bound. Of the two, the inner chloroplast membrane is relatively less permeable. The space limited by the inner membrane of the chloroplast is called the stroma. A number of organised flattened membranous sacs called the **thylakoids**, are present in the stroma (Figure 8.8). Thylakoids are arranged in stacks like the piles of coins called grana (singular: granum) or the intergranal thylakoids. In addition, there are flat membranous tubules called the stroma lamellae connecting the thylakoids of the different grana. The membrane of the thylakoids enclose a space called a lumen. The stroma of the chloroplast contains enzymes required for the synthesis of carbohydrates and proteins. It also contains small, double-stranded circular DNA molecules and ribosomes. Chlorophyll pigments are present in the thylakoids. The ribosomes of the chloroplasts are smaller (70S) than the cytoplasmic ribosomes (80S).

8.5.6 Ribosomes

Ribosomes are the granular structures first observed under the electron microscope as dense particles by George Palade (1953). They are composed of ribonucleic acid (RNA) and proteins and are not surrounded by any membrane.

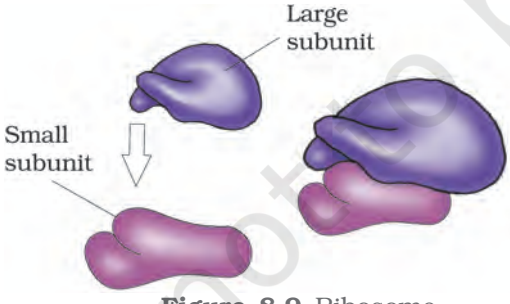

Figure 8.9 Ribosome

The eukaryotic ribosomes are 80S while the prokaryotic ribosomes are 70S. Each ribosome has two subunits, larger and smaller subunits (Fig 8.9). The two subunits of 80S ribosomes are 60S and 40S while that of 70S ribosomes are 50S and 30S. Here 'S' (Svedberg's Unit) stands for the sedimentation coefficient; it is indirectly a measure of density and size. Both 70S and 80S ribosomes are composed of two subunits.

8.5.7 Cytoskeleton

An elaborate network of filamentous proteinaceous structures consisting of microtubules, microfilaments and intermediate filaments present in the cytoplasm is collectively referred to as the **cytoskeleton**. The cytoskeleton in a cell are involved in many functions such as mechanical support, motility, maintenance of the shape of the cell.

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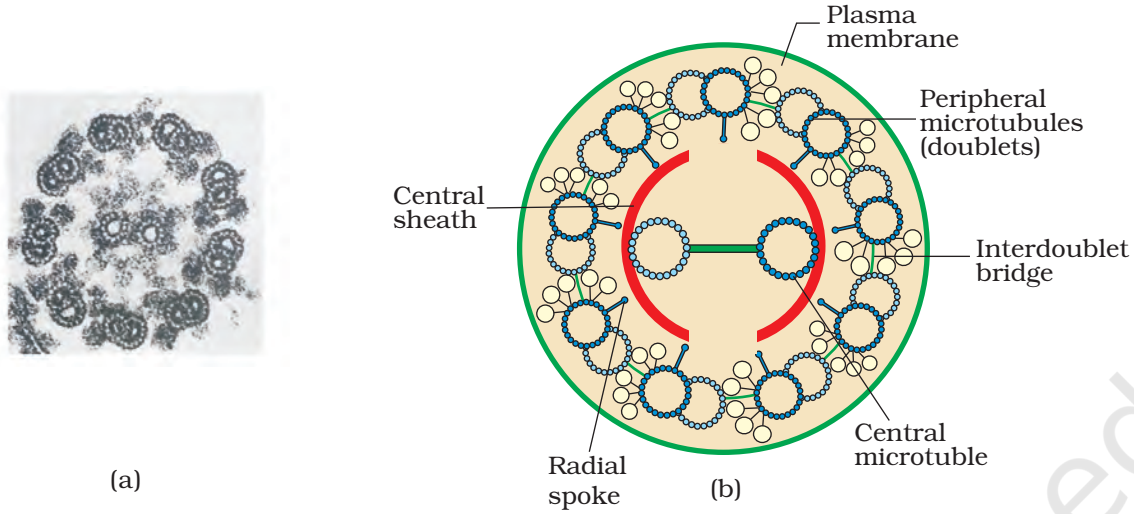

Figure 8.10 Section of cilia/flagella showing different parts : (a) Electron micrograph (b) Diagrammatic representation of internal structure

8.5.8 Cilia and Flagella

Cilia (sing.: cilium) and flagella (sing.: flagellum) are hair-like outgrowths of the cell membrane. Cilia are small structures which work like oars, causing the movement of either the cell or the surrounding fluid. Flagella are comparatively longer and responsible for cell movement. The prokaryotic bacteria also possess flagella but these are structurally different from that of the eukaryotic flagella.

The electron microscopic study of a cilium or the flagellum show that they are covered with plasma membrane. Their core called the **axoneme,** possesses a number of microtubules running parallel to the long axis. The axoneme usually has nine doublets of radially arranged peripheral microtubules, and a pair of centrally located microtubules. Such an arrangement of axonemal microtubules is referred to as the 9+2 array (Figure 8.10). The central tubules are connected by bridges and is also enclosed by a central sheath, which is connected to one of the tubules of each peripheral doublets by a radial spoke. Thus, there are nine radial spokes. The peripheral doublets are also interconnected by linkers. Both the cilium and flagellum emerge from centriole-like structure called the basal bodies.

8.5.9 Centrosome and Centrioles

Centrosome is an organelle usually containing two cylindrical structures called centrioles. They are surrounded by amorphous pericentriolar materials. Both the centrioles in a centrosome lie perpendicular to each other in which each has an organisation like the cartwheel. They are

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made up of nine evenly spaced peripheral fibrils of tubulin protein. Each of the peripheral fibril is a triplet.The adjacent triplets are also linked. The central part of the proximal region of the centriole is also proteinaceous and called the **hub**, which is connected with tubules of the peripheral triplets by radial **spokes** made of protein. The centrioles form the basal body of cilia or flagella, and spindle fibres that give rise to spindle apparatus during cell division in animal cells.

8.5.10 Nucleus

Nucleus as a cell organelle was first described by Robert Brown as early as 1831. Later the material of the nucleus stained by the basic dyes was given the name **chromatin** by Flemming.

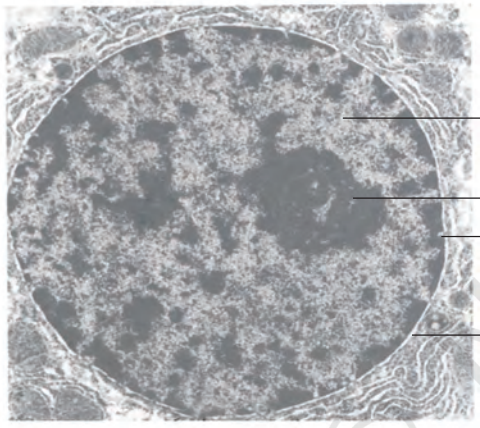

Figure 8.11 Structure of nucleus

The interphase nucleus (nucleus of a cell when it is not dividing) has highly extended and elaborate nucleoprotein fibres called chromatin, nuclear matrix and one or more spherical bodies called **nucleoli** (sing.: nucleolus) (Figure 8.11). Electron microscopy has revealed that the nuclear envelope, which consists of two parallel membranes with a space between (10 to 50 nm) called the **perinuclear space**, forms a barrier between the materials present inside the nucleus and that of the cytoplasm. The outer membrane usually remains continuous with the endoplasmic reticulum and also bears ribosomes on it. At a number of places the nuclear envelope is interrupted by minute pores, which are formed by the fusion of its two membranes. These nuclear pores are the passages through which movement of RNA and protein molecules takes place in both directions between the nucleus and the cytoplasm. Normally, there is only one nucleus per cell, variations in the number of nuclei are also frequently observed. *Can you recollect names of organisms that have more than one nucleus per cell?* Some mature cells even lack nucleus, e.g., erythrocytes of many mammals and sieve tube cells of vascular plants. *Would you consider these cells as 'living'?*

The nuclear matrix or the **nucleoplasm** contains nucleolus and chromatin. The nucleoli are spherical structures present in the nucleoplasm. The content of nucleolus is continuous with the rest of the nucleoplasm as it is not a membrane bound structure. It is a site for active ribosomal RNA synthesis. Larger and more numerous nucleoli are present in cells actively carrying out protein synthesis.

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You may recall that the interphase nucleus has a loose and indistinct network of nucleoprotein fibres called chromatin. But during different stages of cell division, cells show structured **chromosomes** in place of the nucleus. Chromatin contains DNA and some basic proteins called **histones**, some non-histone proteins and also RNA. A single human cell has approximately two metre long thread of DNA distributed among its forty six (twenty three pairs) chromosomes. You will study the details of DNA packaging in the form of a chromosome in class XII.

Every chromosome (visible only in dividing cells) essentially has a primary constriction or the **centromere** on the sides of which disc shaped structures called **kinetochores** are present (Figure 8.12). Centromere holds two chromatids of a chromosome. Based on the position of the centromere, the chromosomes can be classified into four types (Figure 8.13). The **metacentric** chromosome has middle centromere forming two equal arms of the chromosome. The **sub-metacentric** chromosome has centromere slightly away from the middle of the chromosome resulting into one shorter arm and one longer arm. In case of **acrocentric** chromosome the centromere is situated close to its end forming one extremely short and one very long arm, whereas the **telocentric** chromosome has a terminal centromere.

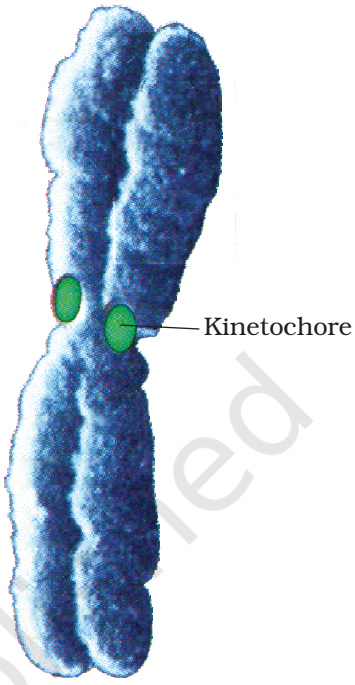

Figure 8.12 Chromosome with kinetochore

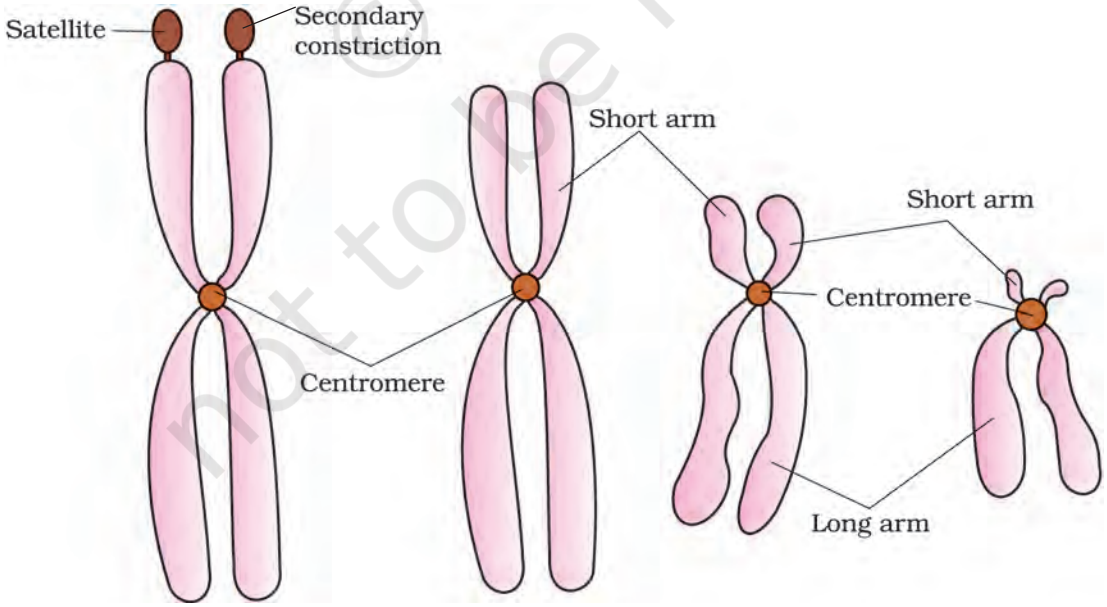

Figure 8.13 Types of chromosomes based on the position of centromere

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Sometimes a few chromosomes have non-staining secondary constrictions at a constant location. This gives the appearance of a small fragment called the **satellite**.

8.5.11 Microbodies

Many membrane bound minute vesicles called microbodies that contain various enzymes, are present in both plant and animal cells.

SUMMARY

All organisms are made of cells or aggregates of cells. Cells vary in their shape, size and activities/functions. Based on the presence or absence of a membrane bound nucleus and other organelles, cells and hence organisms can be named as eukaryotic or prokaryotic.

A typical eukaryotic cell consists of a cell membrane, nucleus and cytoplasm. Plant cells have a cell wall outside the cell membrane. The plasma membrane is selectively permeable and facilitates transport of several molecules. The endomembrane system includes ER, golgi complex, lysosomes and vacuoles. All the cell organelles perform different but specific functions. Centrosome and centriole form the basal body of cilia and flagella that facilitate locomotion. In animal cells, centrioles also form spindle apparatus during cell division. Nucleus contains nucleoli and chromatin network. It not only controls the activities of organelles but also plays a major role in heredity.

Endoplasmic reticulum contains tubules or cisternae. They are of two types: rough and smooth. ER helps in the transport of substances, synthesis of proteins, lipoproteins and glycogen. The golgi body is a membranous organelle composed of flattened sacs. The secretions of cells are packed in them and transported from the cell. Lysosomes are single membrane structures containing enzymes for digestion of all types of macromolecules. Ribosomes are involved in protein synthesis. These occur freely in the cytoplasm or are associated with ER. Mitochondria help in oxidative phosphorylation and generation of adenosine triphosphate. They are bound by double membrane; the outer membrane is smooth and inner one folds into several cristae. Plastids are pigment containing organelles found in plant cells only. In plant cells, chloroplasts are responsible for trapping light energy essential for photosynthesis. The grana, in the plastid, is the site of light reactions and the stroma of dark reactions. The green coloured plastids are chloroplasts, which contain chlorophyll, whereas the other coloured plastids are chromoplasts, which may contain pigments like carotene and xanthophyll. The nucleus is enclosed by nuclear envelope, a double membrane structure with nuclear pores. The inner membrane encloses the nucleoplasm and the chromatin material. Thus, cell is the structural and functional unit of life.

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EXERCISES

1. Which of the following is not correct?
   (a) Robert Brown discovered the cell.
   (b) Schleiden and Schwann formulated the cell theory.
   (c) Virchow explained that cells are formed from pre-existing cells.
   (d) A unicellular organism carries out its life activities within a single cell.
2. New cells generate from
   (a) bacterial fermentation (b) regeneration of old cells
   (c) pre-existing cells (d) abiotic materials
3. Match the following

Column I	Column II
(a) Cristae	(i) Flat membranous sacs in stroma
(b) Cisternae	(ii) Infoldings in mitochondria
(c) Thylakoids	(iii) Disc-shaped sacs in Golgi apparatus

4. Which of the following is correct:
   (a) Cells of all living organisms have a nucleus.
   (b) Both animal and plant cells have a well defined cell wall.
   (c) In prokaryotes, there are no membrane bound organelles.
   (d) Cells are formed *de novo* from abiotic materials.
5. What is a mesosome in a prokaryotic cell? Mention the functions that it performs.
6. How do neutral solutes move across the plasma membrane? Can the polar molecules also move across it in the same way? If not, then how are these transported across the membrane?
7. Name two cell-organelles that are double membrane bound. What are the characteristics of these two organelles? State their functions and draw labelled diagrams of both.
8. What are the characteristics of prokaryotic cells?
9. Multicellular organisms have division of labour. Explain.
10. Cell is the basic unit of life. Discuss in brief.
11. What are nuclear pores? State their function.
12. Both lysosomes and vacuoles are endomembrane structures, yet they differ in terms of their functions. Comment.
13. Describe the structure of the following with the help of labelled diagrams.
    (i) Nucleus (ii) Centrosome
14. What is a centromere? How does the position of centromere form the basis of classification of chromosomes. Support your answer with a diagram showing the position of centromere on different types of chromosomes.

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Chapter 9
Biomolecules

9.1 How to Analyse Chemical Composition?
9.2 Primary and Secondary Metabolites
9.3 Biomacromolecules
9.4 Proteins
9.5 Polysaccharides
9.6 Nucleic Acids
9.7 Structure of Proteins
9.8 Enzymes

There is a wide diversity in living organisms in our biosphere. Now a question that arises in our minds is: Are all living organisms made of the same chemicals, i.e., elements and compounds? You have learnt in chemistry how elemental analysis is performed. If we perform such an analysis on a plant tissue, animal tissue or a microbial paste, we obtain a list of elements like carbon, hydrogen, oxygen and several others and their respective content per unit mass of a living tissue. If the same analysis is performed on a piece of earth's crust as an example of non-living matter, we obtain a similar list. What are the differences between the two lists? In absolute terms, no such differences could be made out. All the elements present in a sample of earth's crust are also present in a sample of living tissue. However, a closer examination reveals that the relative abundance of carbon and hydrogen with respect to other elements is higher in any living organism than in earth's crust (Table 9.1).

9.1 How to Analyse Chemical Composition?

We can continue asking in the same way, what type of organic compounds are found in living organisms? How does one go about finding the answer? To get an answer, one has to perform a chemical analysis. We can take any living tissue (a vegetable or a piece of liver, etc.) and grind it in trichloroacetic acid (Cl_3CCOOH) using a mortar and a pestle. We obtain a thick slurry. If we were to strain this through a cheesecloth or cotton we would obtain two fractions. One is called the filtrate or more technically, the acid-soluble pool, and the second, the retentate or the acid-insoluble fraction. Scientists have found thousands of organic compounds in the acid-soluble pool.

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In higher classes you will learn about how to analyse a living tissue sample and identify a particular organic compound. It will suffice to say here that one extracts the compounds, then subjects the extract to various separation techniques till one has separated a compound from all other compounds. In other words, one isolates and purifies a compound. Analytical techniques, when applied to the compound give us an idea of the molecular formula and the probable structure of the compound. All the carbon compounds that we get from living tissues can be called 'biomolecules'. However, living organisms have also got inorganic elements and compounds in them. How do we know this? A slightly different but destructive experiment has to be done. One weighs a small amount of a living tissue (say a leaf or liver and this is called wet weight) and dry it. All the water, evaporates. The remaining material gives dry weight. Now if the tissue is fully burnt, all the carbon compounds are oxidised to gaseous form (CO_2, water vapour) and are removed. What is remaining is called 'ash'. This ash contains inorganic elements (like calcium, magnesium etc). Inorganic compounds like sulphate, phosphate, etc., are also seen in the acid-soluble fraction. Therefore elemental analysis gives elemental composition of living tissues in the form of hydrogen, oxygen, chlorine, carbon etc. while analysis for compounds gives an idea of the kind of organic (Figure 9.1) and inorganic constituents (Table 9.2) present in living tissues. From a chemistry point of view, one can identify functional groups like aldehydes, ketones, aromatic compounds, etc. But from a biological point of view, we shall classify them into amino acids, nucleotide bases, fatty acids etc.

TABLE 9.1 A Comparison of Elements Present in Non-living and Living Matter*

Element	% Weight of Earth's crust	% Weight of Human body
Hydrogen (H)	0.14	9.5
Carbon (C)	0.03	18.5
Oxygen (O)	46.6	65.0
Nitrogen (N)	very little	3.3
Sulphur (S)	0.03	0.3
Sodium (Na)	2.8	0.2
Calcium (Ca)	3.6	1.5
Magnesium (Mg)	2.1	0.1
Silicon (Si)	27.7	negligible

* Adapted from CNR Rao, *Understanding Chemistry*, Universities Press, Hyderabad.

TABLE 9.2 A List of Representative Inorganic Constituents of Living Tissues

Component	Formula
Sodium	Na^+
Potassium	K^+
Calcium	Ca^{++}
Magnesium	Mg^{++}
Water	H_2O
Compounds	NaCl, $CaCO_3$, PO_4^{3-} , SO_4^{2-}

Amino acids are organic compounds containing an amino group and an acidic group as substituents on the same carbon i.e., the α-carbon. Hence, they are called α-amino acids. They are substituted methanes. There are four substituent groups occupying the four valency positions. These are hydrogen, carboxyl group, amino group and a variable group designated as R group. Based on the nature of R group there are many amino acids. However, those which occur in proteins are only of twenty

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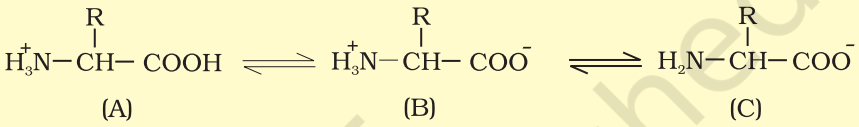
types. The R group in these proteinaceous amino acids could be a hydrogen (the amino acid is called glycine), a methyl group (alanine), hydroxy methyl (serine), etc. Three of the twenty are shown in Figure 9.1.

The chemical and physical properties of amino acids are essentially of the amino, carboxyl and the R functional groups. Based on number of amino and carboxyl groups, there are acidic (e.g., glutamic acid), basic (lysine) and neutral (valine) amino acids. Similarly, there are aromatic amino acids (tyrosine, phenylalanine, tryptophan). A particular property of amino acids is the ionizable nature of $-NH_2$ and –COOH groups. Hence in solutions of different pH, the structure of amino acids changes.



(A) (B) (C)

B is called zwitterionic form.

Lipids are generally water insoluble. They could be simple fatty acids. A fatty acid has a carboxyl group attached to an R group. The R group could be a methyl ($-CH_3$), or ethyl ($-C_2H_5$) or higher number of $-CH_2$ groups (1 carbon to 19 carbons). For example, palmitic acid has 16 carbons including carboxyl carbon. Arachidonic acid has 20 carbon atoms including the carboxyl carbon. Fatty acids could be saturated (without double bond) or unsaturated (with one or more C=C double bonds). Another simple lipid is glycerol which is trihydroxy propane. Many lipids have both glycerol and fatty acids. Here the fatty acids are found esterified with glycerol. They can be then monoglycerides, diglycerides and triglycerides. These are also called fats and oils based on melting point. Oils have lower melting point (e.g., gingelly oil) and hence remain as oil in winters. Can you identify a fat from the market? Some lipids have phosphorous and a phosphorylated organic compound in them. These are phospholipids. They are found in cell membrane. Lecithin is one example. Some tissues especially the neural tissues have lipids with more complex structures.

Living organisms have a number of carbon compounds in which heterocyclic rings can be found. Some of these are nitrogen bases – adenine, guanine, cytosine, uracil, and thymine. When found attached to a sugar, they are called nucleosides. If a phosphate group is also found esterified to the sugar they are called nucleotides. Adenosine, guanosine, thymidine, uridine and cytidine are nucleosides. Adenylic acid, thymidylic acid, guanylic acid, uridylic acid and cytidylic acid are nucleotides. Nucleic acids like DNA and RNA consist of nucleotides only. DNA and RNA function as genetic material.

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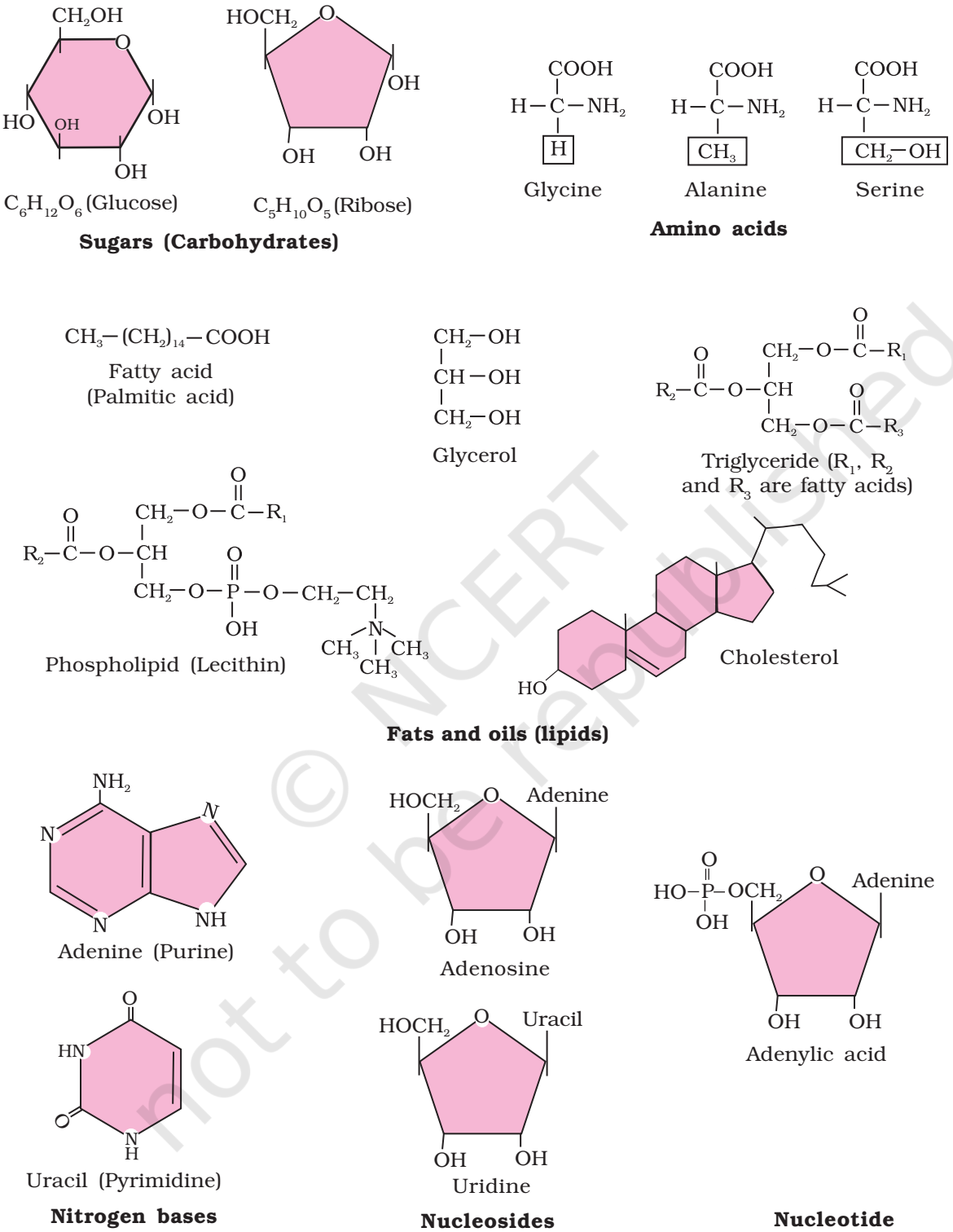

Figure 9.1 Diagrammatic representation of small molecular weight organic compounds in living tissues

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9.2 PRIMARY AND SECONDARY METABOLITES

The most exciting aspect of chemistry deals with isolating thousands of compounds, small and big, from living organisms, determining their structure and if possible synthesising them.

If one were to make a list of biomolecules, such a list would have thousands of organic compounds including amino acids, sugars, etc. For reasons that are given in section 9.10, we can call these biomolecules as 'metabolites'. In animal tissues, one notices the presence of all such categories of compounds shown in Figure 9.1. These are primary metabolites. However, when one analyses plant, fungal and microbial cells, one would see thousands of compounds other than these primary metabolites, e.g. alkaloids, flavonoids, rubber, essential oils, antibiotics, coloured pigments, scents, gums, spices. These are called **secondary metabolites** (Table 9.3). While primary metabolites have identifiable functions and play known roles in normal physiologial processes, we do not at the moment, understand the role or functions of all the 'secondary metabolites' in host organisms. However, many of them are useful to 'human welfare' (e.g., rubber, drugs, spices, scents and pigments). Some secondary metabolites have ecological importance. In the later chapters and years you will learn more about this.

TABLE 9.3 Some Secondary Metabolites

Pigments	Carotenoids, Anthocyanins, etc.
Alkaloids	Morphine, Codeine, etc.
Terpenoides	Monoterpenes, Diterpenes etc.
Essential oils	Lemon grass oil, etc.
Toxins	Abrin, Ricin
Lectins	Concanavalin A
Drugs	Vinblastin, curcumin, etc.
Polymeric substances	Rubber, gums, cellulose

9.3 BIOMACROMOLECULES

There is one feature common to all those compounds found in the acid soluble pool. They have molecular weights ranging from 18 to around 800 daltons (Da) approximately.

The acid insoluble fraction, has only four types of organic compounds i.e., proteins, nucleic acids, polysaccharides and lipids. These classes of compounds with the exception of lipids, have molecular weights in the range of ten thousand daltons and above. For this very reason, biomolecules, i.e., chemical compounds found in living organisms are of two types. One, those which have molecular weights less than one thousand dalton and are usually referred to as micromolecules or simply biomolecules while those which are found in the acid insoluble fraction are called macromolecules or **biomacromolecules**.

The molecules in the insoluble fraction with the exception of lipids are polymeric substances. Then why do lipids, whose molecular weights do not exceed 800 Da, come under acid insoluble fraction, i.e., macromolecular fraction? Lipids are indeed small molecular weight

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compounds and are present not only as such but also arranged into structures like cell membrane and other membranes. When we grind a tissue, we are disrupting the cell structure. Cell membrane and other membranes are broken into pieces, and form vesicles which are not water soluble. Therefore, these membrane fragments in the form of vesicles get separated along with the acid insoluble pool and hence in the macromolecular fraction. Lipids are not strictly macromolecules.

The acid soluble pool represents roughly the cytoplasmic composition. The macromolecules from cytoplasm and organelles become the acid insoluble fraction. Together they represent the entire chemical composition of living tissues or organisms.

In summary if we represent the chemical composition of living tissue from abundance point of view and arrange them class-wise, we observe that water is the most abundant chemical in living organisms (Table 9.4).

TABLE 9.4 Average Composition of Cells

Component	% of the total cellular mass
Water	70-90
Proteins	10-15
Carbohydrates	3
Lipids	2
Nucleic acids	5-7
Ions	1

9.4 PROTEINS

Proteins are polypeptides. They are linear chains of amino acids linked by peptide bonds as shown in Figure 9.3.

Each protein is a polymer of amino acids. As there are 20 types of amino acids (e.g., alanine, cysteine, proline, tryptophan, lysine, etc.), a protein is a heteropolymer and not a homopolymer. A homopolymer has only one type of monomer repeating 'n' number of times. This information about the amino acid content is important as later in your nutrition lessons, you will learn that certain amino acids are essential for our health and they have to be supplied through our diet. Hence, dietary proteins are the source of essential amino acids. Therefore, amino acids can be essential or non-essential. The latter are those which our body can make, while we get essential amino acids through our diet/food. Proteins carry out many functions in living organisms, some transport nutrients across cell membrane, some fight infectious organisms, some are hormones, some are enzymes,

TABLE 9.5 Some Proteins and their Functions

Protein	Functions
Collagen	Intercellular ground substance
Trypsin	Enzyme
Insulin	Hormone
Antibody	Fights infectious agents
Receptor	Sensory reception (smell, taste, hormone, etc.)
GLUT-4	Enables glucose transport into cells

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etc. (Table 9.5). Collagen is the most abundant protein in animal world and Ribulose bisphosphate Carboxylase-Oxygenase (RuBisCO) is the most abundant protein in the whole of the biosphere.

9.5 POLYSACCHARIDES

The acid insoluble pellet also has polysaccharides (carbohydrates) as another class of macromolecules. Polysaccharides are long chains of sugars. They are threads (literally a cotton thread) containing different monosaccharides as building blocks. For example, cellulose is a polymeric polysaccharide consisting of only one type of monosaccharide i.e., glucose. Cellulose is a homopolymer. Starch is a variant of this but present as a store house of energy in plant tissues. Animals have another variant called glycogen. Inulin is a polymer of fructose. In a polysaccharide chain (say glycogen), the right end is called the reducing end and the left end is called the non-reducing end. It has branches as shown in the form of a cartoon (Figure 9.2). Starch forms helical secondary structures. In fact, starch can hold I_2 molecules in the helical portion. The starch-I_2 is blue in colour. Cellulose does not contain complex helices and hence cannot hold I_2.

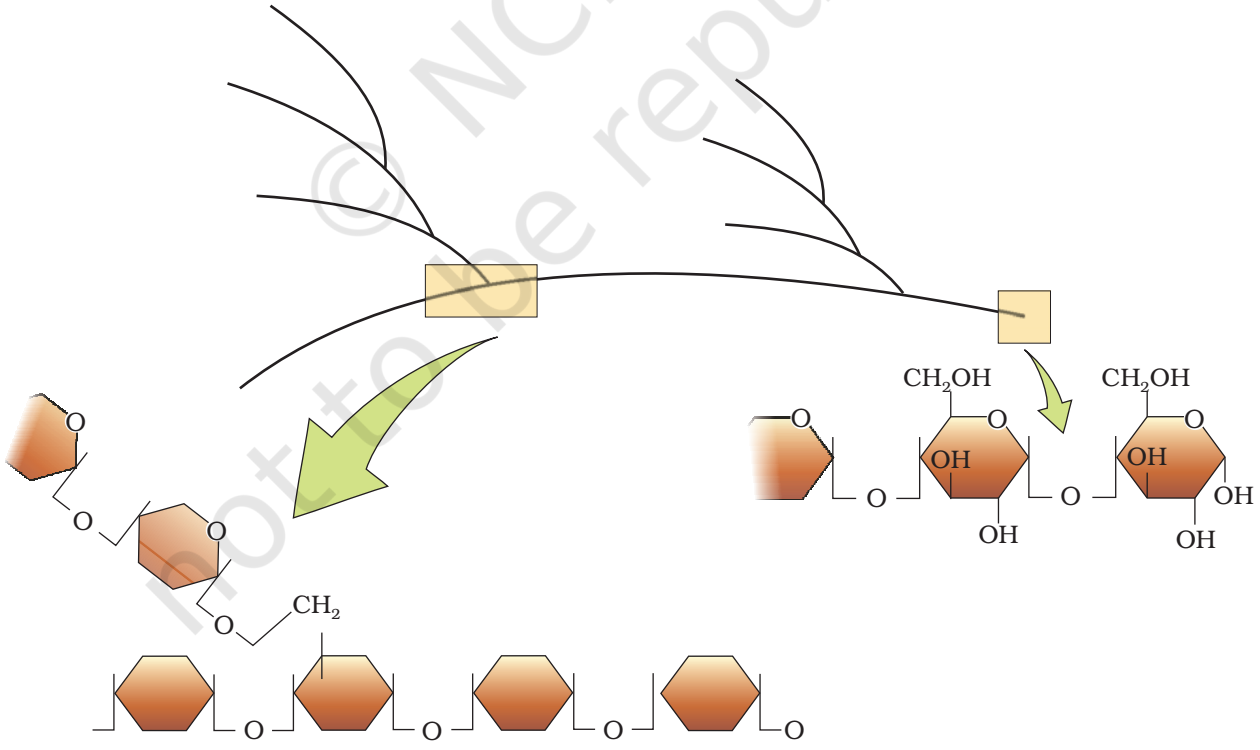

Figure 9.2 Diagrammatic representation of a portion of glycogen

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Plant cell walls are made of cellulose. Paper made from plant pulp and cotton fibre is cellulosic. There are more complex polysaccharides in nature. They have as building blocks, amino-sugars and chemically modified sugars (e.g., glucosamine, N-acetyl galactosamine, etc.). Exoskeletons of arthropods, for example, have a complex polysaccharide called chitin. These complex polysaccharides are mostly homopolymers.

9.6 NUCLEIC ACIDS

The other type of macromolecule that one would find in the acid insoluble fraction of any living tissue is the nucleic acid. These are polynucleotides. Together with polysaccharides and polypeptides these comprise the true macromolecular fraction of any living tissue or cell. For nucleic acids, the building block is a nucleotide. A nucleotide has three chemically distinct components. One is a heterocyclic compound, the second is a monosaccharide and the third a phosphoric acid or phosphate.

As you notice in Figure 9.1, the heterocyclic compounds in nucleic acids are the nitrogenous bases named adenine, guanine, uracil, cytosine, and thymine. Adenine and Guanine are substituted purines while the rest are substituted pyrimidines. The skeletal heterocyclic ring is called as purine and pyrimidine respectively. The sugar found in polynucleotides is either ribose (a monosaccharide pentose) or 2' deoxyribose. A nucleic acid containing deoxyribose is called deoxyribonucleic acid (DNA) while that which contains ribose is called ribonucleic acid (RNA).

9.7 STRUCTURE OF PROTEINS

Proteins, as mentioned earlier, are heteropolymers containing strings of amino acids. Structure of molecules means different things in different contexts. In inorganic chemistry, the structure invariably refers to the molecular formulae (e.g., NaCl, $MgCl_2$, etc.). Organic chemists always write a two dimensional view of the molecules while representing the structure of the molecules (e.g., benzene, naphthalene, etc.). Physicists conjure up the three dimensional views of molecular structures while biologists describe the protein structure at four levels. The sequence of amino acids i.e., the positional information in a protein – which is the first amino acid, which is second, and so on – is called the **primary structure** (Figure 9.3 a) of a protein. A protein is imagined as a line, the left end represented by the first amino acid and the right end represented by the last amino

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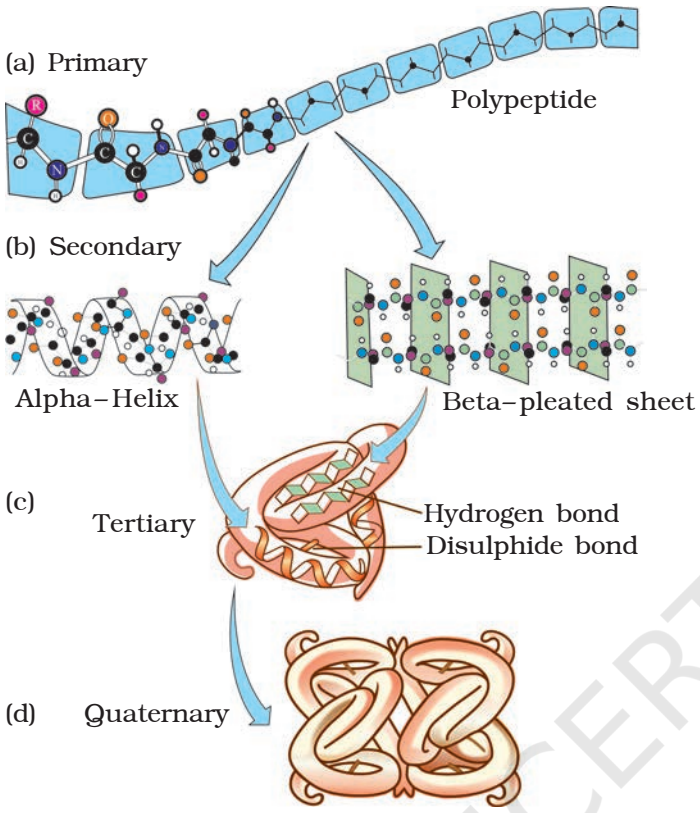

Figure 9.3 Various levels of Protein Structure

acid. The first amino acid is also called as N-terminal amino acid. The last amino acid is called the C-terminal amino acid. A protein thread does not exist throughout as an extended rigid rod. The thread is folded in the form of a helix (similar to a revolving staircase). Of course, only some portions of the protein thread are arranged in the form of a helix. In proteins, only right handed helices are observed. Other regions of the protein thread are folded into other forms in what is called the **secondary structure** (Fig. 9.3 b). In addition, the long protein chain is also folded upon itself like a hollow woolen ball, giving rise to the **tertiary structure** (Fig. 9.3 c). This gives us a 3-dimensional view of a protein. Tertiary structure is absolutely necessary for the many biological activities of proteins.

Some proteins are an assembly of more than one polypeptide or subunits. The manner in which these individual folded polypeptides or subunits are arranged with respect to each other (e.g. linear string of spheres, spheres arranged one upon each other in the form of a cube or plate etc.) is the architecture of a protein otherwise called the **quaternary structure** of a protein (Fig. 9.3 d). Adult human haemoglobin consists of 4 subunits. Two of these are identical to each other. Hence, two subunits of α type and two subunits of β type together constitute the human haemoglobin (Hb).

9.8 ENZYMES

Almost all enzymes are proteins. There are some nucleic acids that behave like enzymes. These are called ribozymes. One can depict an enzyme by a line diagram. An enzyme like any protein has a primary structure, i.e., amino acid sequence of the protein. An enzyme like any protein has the secondary and the tertiary structure. When you look at a tertiary structure

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upon itself, the chain criss-crosses itself and hence, many crevices or pockets are made. One such pocket is the 'active site'. An active site of an enzyme is a crevice or pocket into which the substrate fits. Thus enzymes, through their active site, catalyse reactions at a high rate. Enzyme catalysts differ from inorganic catalysts in many ways, but one major difference needs mention. Inorganic catalysts work efficiently at high temperatures and high pressures, while enzymes get damaged at high temperatures (say above 40°C). However, enzymes isolated from organisms who normally live under extremely high temperatures (e.g., hot vents and sulphur springs), are stable and retain their catalytic power even at high temperatures (upto 80°-90°C). Thermal stability is thus an important quality of such enzymes isolated from thermophilic organisms.

9.8.1 Chemical Reactions

How do we understand these enzymes? Let us first understand a chemical reaction. Chemical compounds undergo two types of changes. A physical change simply refers to a change in shape without breaking of bonds. This is a physical process. Another physical process is a change in state of matter: when ice melts into water, or when water becomes a vapour. These are also physical processes. However, when bonds are broken and new bonds are formed during transformation, this will be called a chemical reaction. For example:

$$Ba(OH)_2 + H_2SO_4 \rightarrow BaSO_4 + 2H_2O$$

is an inorganic chemical reaction. Similarly, hydrolysis of starch into glucose is an organic chemical reaction. Rate of a physical or chemical process refers to the amount of product formed per unit time. It can be expressed as:

$$\text{rate} = \frac{\delta P}{\delta t}$$

Rate can also be called velocity if the direction is specified. Rates of physical and chemical processes are influenced by temperature among other factors. A general rule of thumb is that rate doubles or decreases by half for every 10°C change in either direction. Catalysed reactions proceed at rates vastly higher than that of uncatalysed ones. When enzyme catalysed reactions are observed, the rate would be vastly higher than the same but uncatalysed reaction. For example

$$\underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} \xrightleftharpoons{\text{Carbonic anhydrase}} \underset{\text{carbonic acid}}{H_2CO_3}$$

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In the absence of any enzyme this reaction is very slow, with about 200 molecules of H_2CO_3 being formed in an hour. However, by using the enzyme present within the cytoplasm called carbonic anhydrase, the reaction speeds dramatically with about 600,000 molecules being formed every second. The enzyme has accelerated the reaction rate by about 10 million times. The power of enzymes is incredible indeed!

There are thousands of types of enzymes each catalysing a unique chemical or metabolic reaction. A multistep chemical reaction, when each of the steps is catalysed by the same enzyme complex or different enzymes, is called a metabolic pathway. For example,

$$\text{Glucose} \rightarrow 2 \text{ Pyruvic acid}$$

$$C_6H_{12}O_6 + O_2 \rightarrow 2C_3H_4O_3 + 2H_2O$$

is actually a metabolic pathway in which glucose becomes pyruvic acid through ten different enzyme catalysed metabolic reactions. When you study respiration in Chapter 12, you will study these reactions. At this stage you should know that this very metabolic pathway with one or two additional reactions gives rise to a variety of metabolic end products. In our skeletal muscle, under anaerobic conditions, lactic acid is formed. Under normal aerobic conditions, pyruvic acid is formed. In yeast, during fermentation, the same pathway leads to the production of ethanol (alcohol). Hence, in different conditions different products are possible.

9.8.2 How do Enzymes bring about such High Rates of Chemical Conversions?

To understand this we should study enzymes a little more. We have already understood the idea of an 'active site'. The chemical or metabolic conversion refers to a reaction. The chemical which is converted into a product is called a 'substrate'. Hence enzymes, i.e. proteins with three dimensional structures including an 'active site', convert a substrate (S) into a product (P). Symbolically, this can be depicted as:

$$S \rightarrow P$$

It is now understood that the substrate 'S' has to bind the enzyme at its 'active site' within a given cleft or pocket. The substrate has to diffuse towards the 'active site'. There is thus, an obligatory formation of an 'ES' complex. E stands for enzyme. This complex formation is a transient phenomenon. During the state where substrate is bound to the enzyme active site, a new structure of the substrate called transition state structure is formed. Very soon, after the expected bond breaking/making is completed, the product is released from the active site. In other words, the structure of substrate gets transformed into the structure of product(s). The pathway of this transformation must go through the so-called

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transition state structure. There could be many more 'altered structural states' between the stable substrate and the product. Implicit in this statement is the fact that all other intermediate structural states are unstable. Stability is something related to energy status of the molecule or the structure. Hence, when we look at this pictorially through a graph it looks like something as in Figure 9.4.

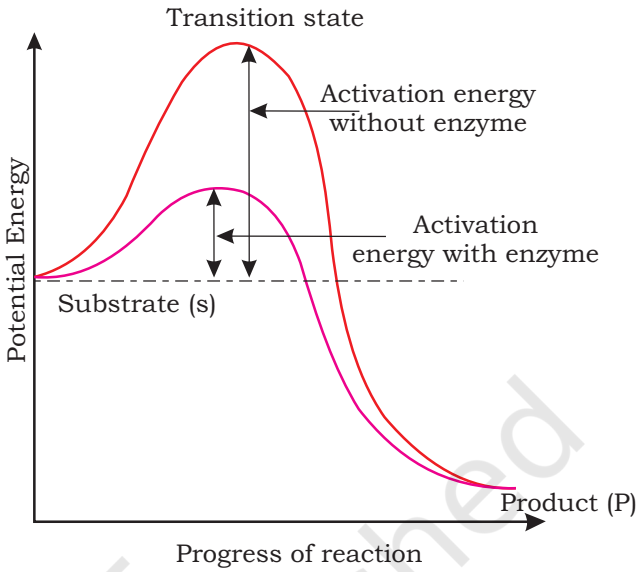

Figure 9.4 Concept of activation energy

The y-axis represents the potential energy content. The x-axis represents the progression of the structural transformation or states through the 'transition state'. You would notice two things. The energy level difference between S and P. If 'P' is at a lower level than 'S', the reaction is an exothermic reaction. One need not supply energy (by heating) in order to form the product. However, whether it is an exothermic or spontaneous reaction or an endothermic or energy requiring reaction, the 'S' has to go through a much higher energy state or transition state. The difference in average energy content of 'S' from that of this transition state is called 'activation energy'.

Enzymes eventually bring down this energy barrier making the transition of 'S' to 'P' more easy.

9.8.3 Nature of Enzyme Action

Each enzyme (E) has a substrate (S) binding site in its molecule so that a highly reactive enzyme-substrate complex (ES) is produced. This complex is short-lived and dissociates into its product(s) P and the unchanged enzyme with an intermediate formation of the enzyme-product complex (EP).

The formation of the ES complex is essential for catalysis.

$$E + S \quad ES \longrightarrow EP \longrightarrow E + P$$

The catalytic cycle of an enzyme action can be described in the following steps:

1. First, the substrate binds to the active site of the enzyme, fitting into the active site.
2. The binding of the substrate induces the enzyme to alter its shape, fitting more tightly around the substrate.
3. The active site of the enzyme, now in close proximity of the substrate breaks the chemical bonds of the substrate and the new enzyme- product complex is formed.

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4. The enzyme releases the products of the reaction and the free enzyme is ready to bind to another molecule of the substrate and run through the catalytic cycle once again.

9.8.4 Factors Affecting Enzyme Activity

The activity of an enzyme can be affected by a change in the conditions which can alter the tertiary structure of the protein. These include temperature, pH, change in substrate concentration or binding of specific chemicals that regulate its activity.

Temperature and pH

Enzymes generally function in a narrow range of temperature and pH (Figure 9.5). Each enzyme shows its highest activity at a particular temperature and pH called the optimum temperature and optimum pH. Activity declines both below and above the optimum value. Low temperature preserves the enzyme in a temporarily inactive state whereas high temperature destroys enzymatic activity because proteins are denatured by heat.

Concentration of Substrate

With the increase in substrate concentration, the velocity of the enzymatic reaction rises at first. The reaction ultimately reaches a maximum velocity (V_{max}) which is not exceeded by any further rise in concentration of the substrate. This is because the enzyme molecules are fewer than the substrate molecules and after saturation of these molecules, there are no free enzyme molecules to bind with the additional substrate molecules (Figure 9.5).

The activity of an enzyme is also sensitive to the presence of specific chemicals that bind to the enzyme. When the binding of the chemical

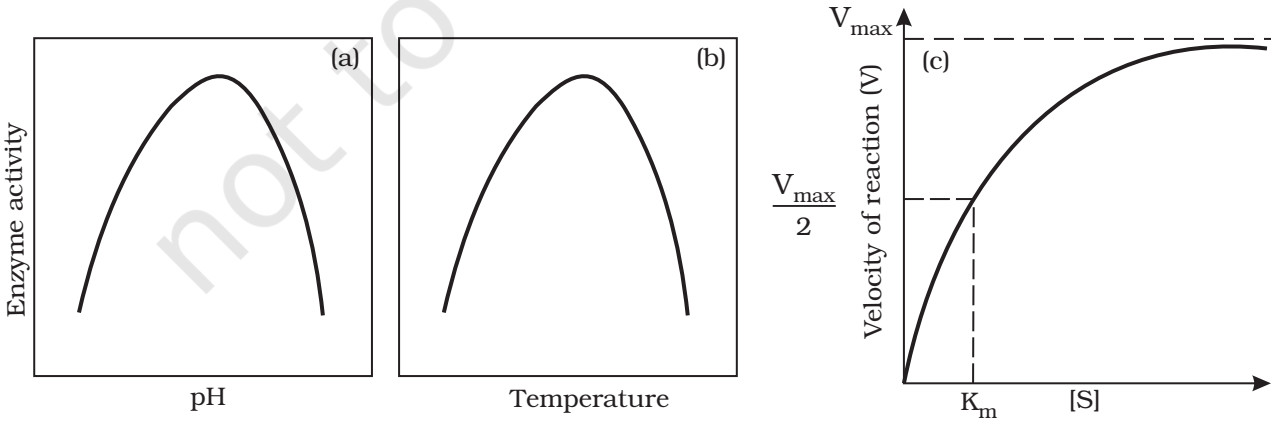

Figure 9.5 Effect of change in : (a) pH (b) Temperature and (c) Concentration of substrate on enzyme activity

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shuts off enzyme activity, the process is called **inhibition** and the chemical is called an **inhibitor**.

When the inhibitor closely resembles the substrate in its molecular structure and inhibits the activity of the enzyme, it is known as **competitive inhibitor**. Due to its close structural similarity with the substrate, the inhibitor competes with the substrate for the substrate-binding site of the enzyme. Consequently, the substrate cannot bind and as a result, the enzyme action declines, e.g., inhibition of succinic dehydrogenase by malonate which closely resembles the substrate succinate in structure. Such competitive inhibitors are often used in the control of bacterial pathogens.

9.8.5 Classification and Nomenclature of Enzymes

Thousands of enzymes have been discovered, isolated and studied. Most of these enzymes have been classified into different groups based on the type of reactions they catalyse. Enzymes are divided into 6 classes each with 4-13 subclasses and named accordingly by a four-digit number.

Oxidoreductases/dehydrogenases: Enzymes which catalyse oxidoreduction between two substrates S and S' e.g.,

$$\text{S reduced} + \text{S' oxidised} \longrightarrow \text{S oxidised} + \text{S' reduced.}$$

Transferases: Enzymes catalysing a transfer of a group, G (other than hydrogen) between a pair of substrate S and S' e.g.,

$$\text{S - G} + \text{S'} \longrightarrow \text{S} + \text{S' - G}$$

Hydrolases: Enzymes catalysing hydrolysis of ester, ether, peptide, glycosidic, C-C, C-halide or P-N bonds.

Lyases: Enzymes that catalyse removal of groups from substrates by mechanisms other than hydrolysis leaving double bonds.

$$\begin{array}{ccc} X & & Y \\ | & & | \\ C & - & C \end{array} \longrightarrow X - Y + C = C$$

Isomerases: Includes all enzymes catalysing inter-conversion of optical, geometric or positional isomers.

Ligases: Enzymes catalysing the linking together of 2 compounds, e.g., enzymes which catalyse joining of C-O, C-S, C-N, P-O etc. bonds.

9.8.6 Co-factors

Enzymes are composed of one or several polypeptide chains. However, there are a number of cases in which non-protein constituents called co-factors are bound to the the enzyme to make the enzyme catalytically

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active. In these instances, the protein portion of the enzymes is called the apoenzyme. Three kinds of cofactors may be identified: prosthetic groups, co-enzymes and metal ions.

Prosthetic groups are organic compounds and are distinguished from other cofactors in that they are tightly bound to the apoenzyme. For example, in peroxidase and catalase, which catalyze the breakdown of hydrogen peroxide to water and oxygen, haem is the prosthetic group and it is a part of the active site of the enzyme.

Co-enzymes are also organic compounds but their association with the apoenzyme is only transient, usually occurring during the course of catalysis. Furthermore, co-enzymes serve as co-factors in a number of different enzyme catalyzed reactions. The essential chemical components of many coenzymes are vitamins, e.g., coenzyme nicotinamide adenine dinucleotide (NAD) and NADP contain the vitamin niacin.

A number of enzymes require metal ions for their activity which form coordination bonds with side chains at the active site and at the same time form one or more cordination bonds with the substrate, e.g., zinc is a cofactor for the proteolytic enzyme carboxypeptidase.

Catalytic activity is lost when the co-factor is removed from the enzyme which testifies that they play a crucial role in the catalytic activity of the enzyme.

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SUMMARY

Although there is a bewildering diversity of living organisms, their chemical composition and metabolic reactions appear to be remarkably similar. The elemental composition of living tissues and non-living matter appear also to be similar when analysed qualitatively. However, a closer examination reveals that the relative abundance of carbon, hydrogen and oxygen is higher in living systems when compared to inanimate matter. The most abundant chemical in living organisms is water. There are thousands of small molecular weight (<1000 Da) biomolecules. Amino acids, monosaccharide and disaccharide sugars, fatty acids, glycerol, nucleotides, nucleosides and nitrogen bases are some of the organic compounds seen in living organisms. There are 20 types of amino acids and 5 types of nucleotides. Fats and oils are glycerides in which fatty acids are esterified to glycerol. Phospholipids contain, in addition, a phosphorylated nitrogenous compound.

Only three types of macromolecules, i.e., proteins, nucleic acids and polysaccharides are found in living systems. Lipids, because of their association with membranes separate in the macromolecular fraction. Biomacromolecules are polymers. They are made of building blocks which are different. Proteins are heteropolymers made of amino acids. Nucleic acids (RNA and DNA) are composed of nucleotides. Biomacromolecules have a hierarchy of structures –

primary, secondary, tertiary and quaternary. Nucleic acids serve as genetic material. Polysaccharides are components of cell wall in plants, fungi and also of the exoskeleton of arthropods. They also are storage forms of energy (e.g., starch and glycogen). Proteins serve a variety of cellular functions. Many of them are enzymes, some are antibodies, some are receptors, some are hormones and some others are structural proteins. Collagen is the most abundant protein in animal world and Ribulose bisphosphate Carboxylase-Oxygenase (RuBisCO) is the most abundant protein in the whole of the biosphere.

Enzymes are proteins which catalyse biochemical reactions in the cells. Ribozymes are nucleic acids with catalytic power. Proteinaceous enzymes exhibit substrate specificity, require optimum temperature and pH for maximal activity. They are denatured at high temperatures. Enzymes lower activation energy of reactions and enhance greatly the rate of the reactions. Nucleic acids carry hereditary information and are passed on from parental generation to progeny.

EXERCISES

1. What are macromolecules? Give examples.
2. What is meant by tertiary structure of proteins?
3. Find and write down structures of 10 interesting small molecular weight biomolecules. Find if there is any industry which manufactures the compounds by isolation. Find out who are the buyers.
4. Find out and make a list of proteins used as therapeutic agents. Find other applications of proteins (e.g., Cosmetics etc.)
5. Explain the composition of triglyceride.
6. Can you attempt building models of biomolecules using commercially available atomic models (Ball and Stick models).
7. Draw the structure of the amino acid, alanine.
8. What are gums made of? Is Fevicol different?
9. Find out a qualitative test for proteins, fats and oils, amino acids and test any fruit juice, saliva, sweat and urine for them.
10. Find out how much cellulose is made by all the plants in the biosphere and compare it with how much of paper is manufactured by man and hence what is the consumption of plant material by man annually. What a loss of vegetation!
11. Describe the important properties of enzymes.

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Chapter 10
Cell Cycle and Cell Division

10.1 *Cell Cycle*

10.2 *M Phase*

10.3 *Significance of Mitosis*

10.4 *Meiosis*

10.5 *Significance of Meiosis*

Are you aware that all organisms, even the largest, start their life from a single cell? You may wonder how a single cell then goes on to form such large organisms. Growth and reproduction are characteristics of cells, indeed of all living organisms. All cells reproduce by dividing into two, with each parental cell giving rise to two daughter cells each time they divide. These newly formed daughter cells can themselves grow and divide, giving rise to a new cell population that is formed by the growth and division of a single parental cell and its progeny. In other words, such cycles of growth and division allow a single cell to form a structure consisting of millions of cells.

10.1 Cell Cycle

Cell division is a very important process in all living organisms. During the division of a cell, DNA replication and cell growth also take place. All these processes, i.e., cell division, DNA replication, and cell growth, hence, have to take place in a coordinated way to ensure correct division and formation of progeny cells containing intact genomes. The sequence of events by which a cell duplicates its genome, synthesises the other constituents of the cell and eventually divides into two daughter cells is termed **cell cycle.** Although cell growth (in terms of cytoplasmic increase) is a continuous process, DNA synthesis occurs only during one specific stage in the cell cycle. The replicated chromosomes (DNA) are then distributed to daughter nuclei by a complex series of events during cell division. These events are themselves under genetic control.

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10.1.1 Phases of Cell Cycle

A typical eukaryotic cell cycle is illustrated by human cells in culture. These cells divide once in approximately every 24 hours (Figure 10.1). However, this duration of cell cycle can vary from organism to organism and also from cell type to cell type. Yeast for example, can progress through the cell cycle in only about 90 minutes.

The cell cycle is divided into two basic phases:

- **Interphase**
- **M Phase (Mitosis phase)**

The M Phase represents the phase when the actual cell division or mitosis occurs and the interphase represents the phase between two successive M phases. It is significant to note that in the 24 hour average duration of cell cycle of a human cell, cell division proper lasts for only about an hour. The interphase lasts more than 95% of the duration of cell cycle.

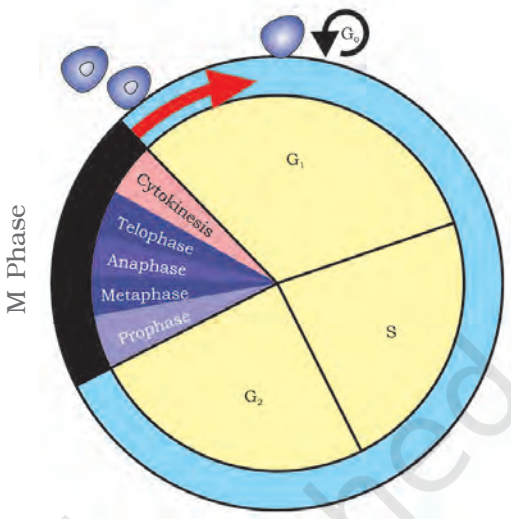

Figure 10.1 A diagrammatic view of cell cycle indicating formation of two cells from one cell

The M Phase starts with the nuclear division, corresponding to the separation of daughter chromosomes **(karyokinesis)** and usually ends with division of cytoplasm **(cytokinesis).** The interphase, though called the resting phase, is the time during which the cell is preparing for division by undergoing both cell growth and DNA replication in an orderly manner. The interphase is divided into three further phases:

- **G_1 phase (Gap 1)**
- **S phase (Synthesis)**
- **G_2 phase (Gap 2)**

G_1 phase corresponds to the interval between mitosis and initiation of DNA replication. During G_1 phase, the cell is metabolically active and continuously grows but does not replicate its DNA. S or **synthesis** phase marks the period during which DNA synthesis or replication takes place. During this time the amount of DNA per cell doubles. If the initial amount of DNA is denoted as 2C then it increases to 4C. However, there is no increase in the chromosome number; if the cell had diploid or 2n number of chromosomes at G_1, even after S phase the number of chromosomes remains the same, i.e., 2n.

In animal cells, during the S phase, DNA replication begins in the nucleus, and the centriole duplicates in the cytoplasm. During the G_2 phase, proteins are synthesised in preparation for mitosis while cell growth continues.

How do plants and animals continue to grow all their lives? Do all cells in a plant divide all the time? Do you think all cells continue to divide in all plants and animals? Can you tell the name and the location of tissues having cells that divide all their life in higher plants? Do animals have similar meristematic tissues?

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You have studied mitosis in onion root tip cells. It has 16 chromosomes in each cell. Can you tell how many chromosomes will the cell have at G_1 phase, after S phase, and after M phase? Also, what will be the DNA content of the cells at G_1, after S and at G_2, if the content after M phase is 2C?

Some cells in the adult animals do not appear to exhibit division (e.g., heart cells) and many other cells divide only occasionally, as needed to replace cells that have been lost because of injury or cell death. These cells that do not divide further exit G_1 phase to enter an inactive stage called ***quiescent stage (G_0)*** of the cell cycle. Cells in this stage remain metabolically active but no longer proliferate unless called on to do so depending on the requirement of the organism.

In animals, mitotic cell division is only seen in the diploid somatic cells. However, there are few exceptions to this where haploid cells divide by mitosis, for example, male honey bees. Against this, the plants can show mitotic divisions in both haploid and diploid cells. From your recollection of examples of alternation of generations in plants (Chapter 3) identify plant species and stages at which mitosis is seen in haploid cells.

10.2 M PHASE

This is the most dramatic period of the cell cycle, involving a major reorganisation of virtually all components of the cell. Since the number of chromosomes in the parent and progeny cells is the same, it is also called as ***equational division.*** Though for convenience mitosis has been divided into four stages of nuclear division (karyokinesis), it is very essential to understand that cell division is a progressive process and very clear-cut lines cannot be drawn between various stages. Karyokinesis involves following four stages:

- ***Prophase***
- ***Metaphase***
- ***Anaphase***
- ***Telophase***

10.2.1 Prophase

Prophase which is the first stage of karyokinesis of mitosis follows the S and G_2 phases of interphase. In the S and G_2 phases, the new DNA molecules formed are not distinct but intertwined. Prophase is marked by the initiation of condensation of chromosomal material. The chromosomal material becomes untangled during the process of chromatin condensation (Figure 10.2 a). The centrosome, which had undergone duplication during S phase of interphase, now begins to move towards opposite poles of the cell. The completion of prophase can thus be marked by the following characteristic events:

- Chromosomal material condenses to form compact mitotic chromosomes. Chromosomes are seen to be composed of two chromatids attached together at the centromere.
- Centrosome which had undergone duplication during interphase, begins to move towards opposite poles of the cell. Each centrosome radiates out microtubules called asters. The two asters together with spindle fibres forms mitotic apparatus.

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Cells at the end of prophase, when viewed under the microscope, do not show golgi complexes, endoplasmic reticulum, nucleolus and the nuclear envelope.

10.2.2 Metaphase

The complete disintegration of the nuclear envelope marks the start of the second phase of mitosis, hence the chromosomes are spread through the cytoplasm of the cell. By this stage, condensation of chromosomes is completed and they can be observed clearly under the microscope. This then, is the stage at which morphology of chromosomes is most easily studied. At this stage, metaphase chromosome is made up of two sister chromatids, which are held together by the centromere (Figure 10.2 b). Small disc-shaped structures at the surface of the centromeres are called kinetochores. These structures serve as the sites of attachment of spindle fibres to the chromosomes that are moved into position at the centre of the cell. Hence, the metaphase is characterised by all the chromosomes coming to lie at the equator with one chromatid of each chromosome connected by its kinetochore to spindle fibres from one pole and its sister chromatid connected by its kinetochore to spindle fibres from the opposite pole (Figure 10.2 b). The plane of alignment of the chromosomes at metaphase is referred to as the **metaphase plate.** The key features of metaphase are:

- Spindle fibres attach to kinetochores of chromosomes.
- Chromosomes are moved to spindle equator and get aligned along metaphase plate through spindle fibres to both poles.

10.2.3 Anaphase

At the onset of anaphase, each chromosome arranged at the metaphase plate is split simultaneously and the two daughter chromatids, now referred to as daughter chromosomes of the future daughter nuclei, begin their migration towards the two opposite poles. As each chromosome moves away from the equatorial plate, the centromere of each chromosome remains directed towards the pole and hence at the leading edge, with the arms of the chromosome trailing behind (Figure 10.2 c). Thus, anaphase stage is characterised by

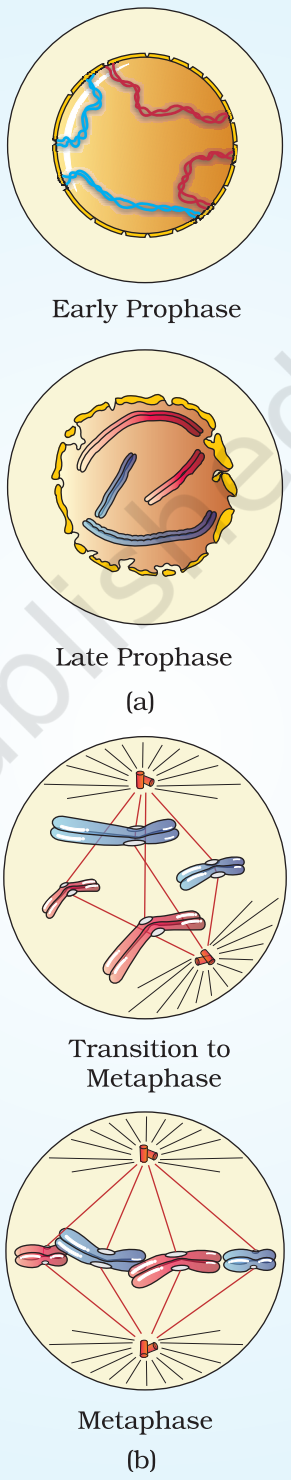

Figure 10.2 a and b : A diagrammatic view of stages in mitosis

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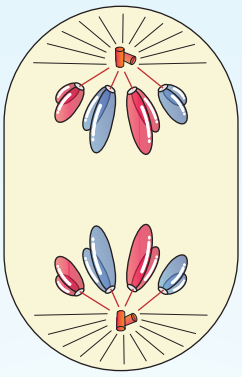
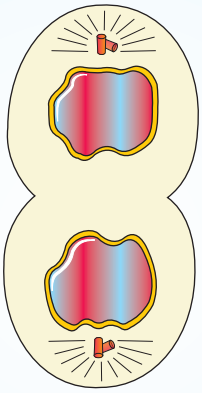


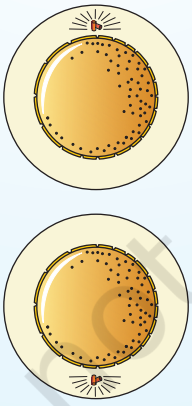
Anaphase

(c)



Telophase

(d)



Interphase

(e)

Figure 10.2 c to e : A diagrammatic view of stages in Mitosis

the following key events:

- Centromeres split and chromatids separate.
- Chromatids move to opposite poles.

10.2.4 Telophase

At the beginning of the final stage of karyokinesis, i.e., telophase, the chromosomes that have reached their respective poles decondense and lose their individuality. The individual chromosomes can no longer be seen and each set of chromatin material tends to collect at each of the two poles (Figure 10.2 d). This is the stage which shows the following key events:

- Chromosomes cluster at opposite spindle poles and their identity is lost as discrete elements.
- Nuclear envelope develops around the chromosome clusters at each pole forming two daughter nuclei.
- Nucleolus, golgi complex and ER reform.

10.2.5 Cytokinesis

Mitosis accomplishes not only the segregation of duplicated chromosomes into daughter nuclei (karyokinesis), but the cell itself is divided into two daughter cells by the separation of cytoplasm called cytokinesis at the end of which cell division gets completed (Figure 10.2 e). In an animal cell, this is achieved by the appearance of a furrow in the plasma membrane. The furrow gradually deepens and ultimately joins in the centre dividing the cell cytoplasm into two. Plant cells however, are enclosed by a relatively inextensible cell wall, thererfore they undergo cytokinesis by a different mechanism. In plant cells, wall formation starts in the centre of the cell and grows outward to meet the existing lateral walls. The formation of the new cell wall begins with the formation of a simple precursor, called the **cell-plate** that represents the middle lamella between the walls of two adjacent cells. At the time of cytoplasmic division, organelles like mitochondria and plastids get distributed between the two daughter cells. In some organisms karyokinesis is not followed by cytokinesis as a result of which multinucleate condition arises leading to the formation of syncytium (e.g., liquid endosperm in coconut).

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10.3 Significance of Mitosis

Mitosis or the equational division is usually restricted to the diploid cells only. However, in some lower plants and in some social insects haploid cells also divide by mitosis. It is very essential to understand the significance of this division in the life of an organism. Are you aware of some examples where you have studied about haploid and diploid insects?

Mitosis usually results in the production of diploid daughter cells with identical genetic complement. The growth of multicellular organisms is due to mitosis. Cell growth results in disturbing the ratio between the nucleus and the cytoplasm. It therefore becomes essential for the cell to divide to restore the nucleo-cytoplasmic ratio. A very significant contribution of mitosis is cell repair. The cells of the upper layer of the epidermis, cells of the lining of the gut, and blood cells are being constantly replaced. Mitotic divisions in the meristematic tissues – the apical and the lateral cambium, result in a continuous growth of plants throughout their life.

10.4 Meiosis

The production of offspring by sexual reproduction includes the fusion of two gametes, each with a complete haploid set of chromosomes. Gametes are formed from specialised diploid cells. This specialised kind of cell division that reduces the chromosome number by half results in the production of haploid daughter cells. This kind of division is called **meiosis.** Meiosis ensures the production of haploid phase in the life cycle of sexually reproducing organisms whereas fertilisation restores the diploid phase. We come across meiosis during gametogenesis in plants and animals. This leads to the formation of haploid gametes. The key features of meiosis are as follows:

- Meiosis involves two sequential cycles of nuclear and cell division called **meiosis I** and **meiosis II** but only a single cycle of DNA replication.
- Meiosis I is initiated after the parental chromosomes have replicated to produce identical sister chromatids at the S phase.
- Meiosis involves pairing of homologous chromosomes and recombination between non-sister chromatids of homologous chromosomes.
- Four haploid cells are formed at the end of meiosis II.

Meiotic events can be grouped under the following phases:

Meiosis I	Meiosis II
Prophase I	Prophase II
Metaphase I	Metaphase II
Anaphase I	Anaphase II
Telophase I	Telophase II

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10.4.1 Meiosis I

Prophase I: Prophase of the first meiotic division is typically longer and more complex when compared to prophase of mitosis. It has been further subdivided into the following five phases based on chromosomal behaviour, i.e., Leptotene, Zygotene, Pachytene, Diplotene and Diakinesis.

During **leptotene** stage the chromosomes become gradually visible under the light microscope. The compaction of chromosomes continues throughout leptotene. This is followed by the second stage of prophase I called **zygotene**. During this stage, chromosomes start pairing together and this process of association is called synapsis. Such paired chromosomes are called homologous chromosomes. Electron micrographs of this stage, indicate that chromosome synapsis is accompanied by the formation of complex structure called **synaptonemal complex.** The complex formed by a pair of synapsed homologous chromosomes is called a **bivalent** or a tetrad. However, these are more clearly visible at the next stage. The first two stages of prophase I are relatively short-lived compared to the next stage that is **pachytene**. During this stage, the four chromatids of each bivalent chromosomes becomes distinct and clearly appear as tetrads. This stage is characterised by the appearance of recombination nodules, the sites at which crossing over occurs between non-sister chromatids of the homologous chromosomes. Crossing over is the exchange of genetic material between two homologous chromosomes. Crossing over is also an enzyme-mediated process and the enzyme involved is called recombinase. Crossing over leads to recombination of genetic material on the two chromosomes. Recombination between homologous chromosomes is completed by the end of pachytene, leaving the chromosomes linked at the sites of crossing over.

The beginning of **diplotene** is recognised by the dissolution of the synaptonemal complex and the tendency of the recombined homologous chromosomes of the bivalents to separate from each other except at the sites of crossovers. These X-shaped structures, are called **chiasmata.** In oocytes of some vertebrates, diplotene can last for months or years.

The final stage of meiotic prophase I is **diakinesis.** This is marked by terminalisation of chiasmata. During this phase the chromosomes are fully condensed and the meiotic spindle is assembled to prepare the homologous chromosomes for separation. By the end of diakinesis, the nucleolus disappears and the nuclear envelope also breaks down. Diakinesis represents transition to metaphase.

Metaphase I: The bivalent chromosomes align on the equatorial plate (Figure 10.3). The microtubules from the opposite poles of the spindle attach to the kinetochore of homologous chromosomes.

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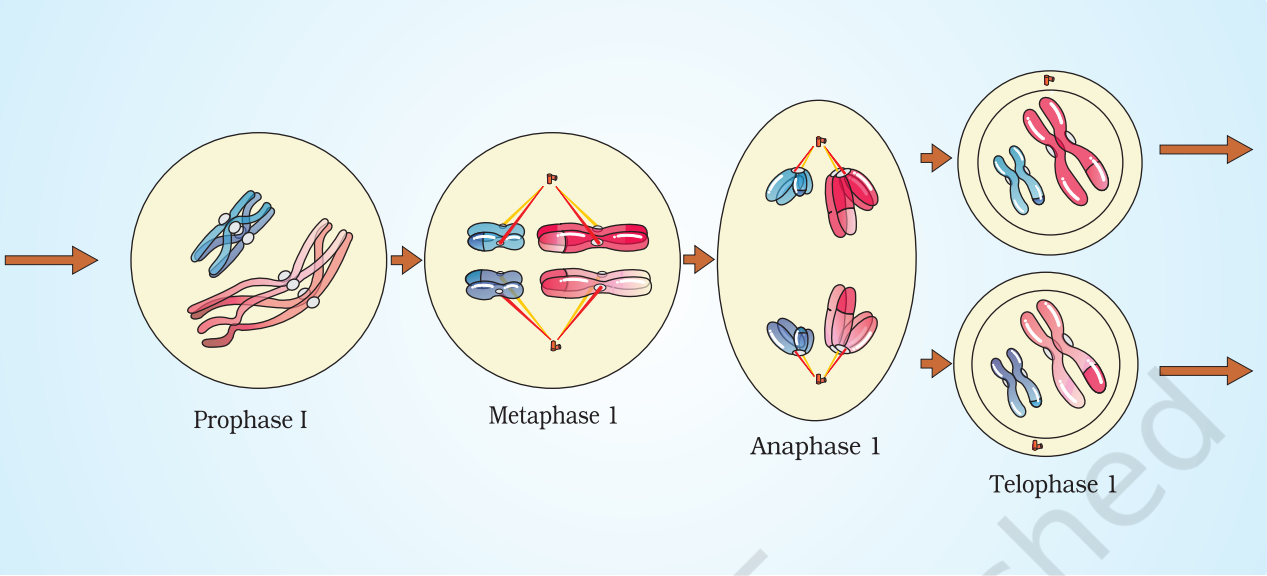

Figure 10.3 Stages of Meiosis I

Anaphase I: The homologous chromosomes separate, while sister chromatids remain associated at their centromeres (Figure 10.3).

Telophase I: The nuclear membrane and nucleolus reappear, cytokinesis follows and this is called as dyad of cells (Figure 10.3). Although in many cases the chromosomes do undergo some dispersion, they do not reach the extremely extended state of the interphase nucleus. The stage between the two meiotic divisions is called interkinesis and is generally short lived. There is no replication of DNA during interkinesis. Interkinesis is followed by prophase II, a much simpler prophase than prophase I.

10.4.2 Meiosis II

Prophase II: Meiosis II is initiated immediately after cytokinesis, usually before the chromosomes have fully elongated. In contrast to meiosis I, meiosis II resembles a normal mitosis. The nuclear membrane disappears by the end of prophase II (Figure 10.4). The chromosomes again become compact.

Metaphase II: At this stage, the chromosomes align at the equator and the microtubules from opposite poles of the spindle get attached to the kinetochores (Figure 10.4) of sister chromatids.

Anaphase II: It begins with the simultaneous splitting of the centromere of each chromosome (which was holding the sister chromatids together), allowing them to move toward opposite poles of the cell (Figure 10.4) by shortening of microtubules attached to kinetochores.

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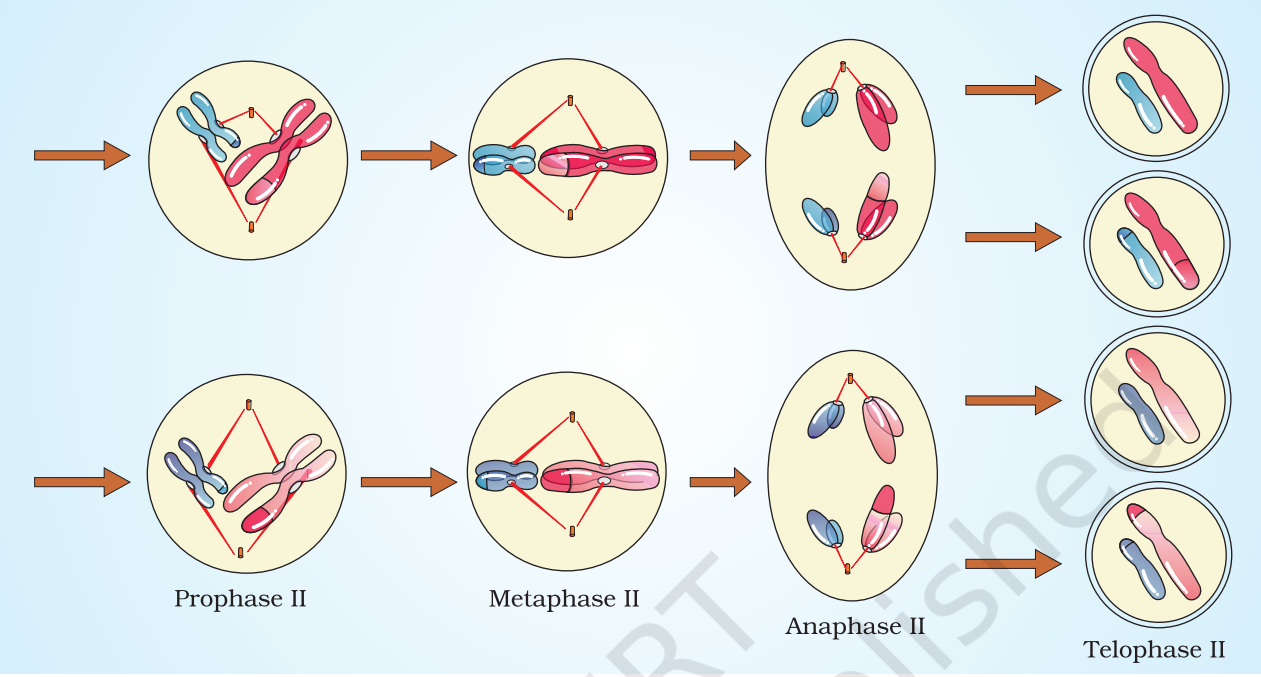

Figure 10.4 Stages of Meiosis II

Telophase II: Meiosis ends with telophase II, in which the two groups of chromosomes once again get enclosed by a nuclear envelope; cytokinesis follows resulting in the formation of tetrad of cells i.e., four haploid daughter cells (Figure 10.4).

10.5 Significance of Meiosis

Meiosis is the mechanism by which conservation of specific chromosome number of each species is achieved across generations in sexually reproducing organisms, even though the process, per se, paradoxically, results in reduction of chromosome number by half. It also increases the genetic variability in the population of organisms from one generation to the next. Variations are very important for the process of evolution.

Summary

According to the cell theory, cells arise from preexisting cells. The process by which this occurs is called cell division. Any sexually reproducing organism starts its life cycle from a single-celled zygote. Cell division does not stop with the formation of the mature organism but continues throughout its life cycle.

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The stages through which a cell passes from one division to the next is called the cell cycle. Cell cycle is divided into two phases called (i) Interphase – a period of preparation for cell division, and (ii) Mitosis (M phase) – the actual period of cell division. Interphase is further subdivided into G_1, S and G_2. G_1 phase is the period when the cell grows and carries out normal metabolism. Most of the organelle duplication also occurs during this phase. S phase marks the phase of DNA replication and chromosome duplication. G_2 phase is the period of cytoplasmic growth. Mitosis is also divided into four stages namely prophase, metaphase, anaphase and telophase. Chromosome condensation occurs during prophase. Simultaneously, the centrioles move to the opposite poles. The nuclear envelope and the nucleolus disappear and the spindle fibres start appearing. Metaphase is marked by the alignment of chromosomes at the equatorial plate. During anaphase the centromeres divide and the chromatids start moving towards the two opposite poles. Once the chromatids reach the two poles, the chromosomal elongation starts, nucleolus and the nuclear membrane reappear. This stage is called the telophase. Nuclear division is then followed by the cytoplasmic division and is called cytokinesis. Mitosis thus, is the equational division in which the chromosome number of the parent is conserved in the daughter cell.

In contrast to mitosis, meiosis occurs in the diploid cells, which are destined to form gametes. It is called the reduction division since it reduces the chromosome number by half while making the gametes. In sexual reproduction when the two gametes fuse the chromosome number is restored to the value in the parent. Meiosis is divided into two phases – meiosis I and meiosis II. In the first meiotic division the homologous chromosomes pair to form bivalents, and undergo crossing over. Meiosis I has a long prophase, which is divided further into five phases. These are leptotene, zygotene, pachytene, diplotene and diakinesis. During metaphase I the bivalents arrange on the equatorial plate. This is followed by anaphase I in which homologous chromosomes move to the opposite poles with both their chromatids. Each pole receives half the chromosome number of the parent cell. In telophase I, the nuclear membrane and nucleolus reappear. Meiosis II is similar to mitosis. During anaphase II the sister chromatids separate. Thus at the end of meiosis four haploid cells are formed.

EXERCISES

1. What is the average cell cycle span for a mammalian cell?
2. Distinguish cytokinesis from karyokinesis.
3. Describe the events taking place during interphase.
4. What is G_o (quiescent phase) of cell cycle?

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5. Why is mitosis called equational division?
6. Name the stage of cell cycle at which one of the following events occur:
   (i) Chromosomes are moved to spindle equator.
   (ii) Centromere splits and chromatids separate.
   (iii) Pairing between homologous chromosomes takes place.
   (iv) Crossing over between homologous chromosomes takes place.
7. Describe the following:
   (a) synapsis (b) bivalent (c) chiasmata
   Draw a diagram to illustrate your answer.
8. How does cytokinesis in plant cells differ from that in animal cells?
9. Find examples where the four daughter cells from meiosis are equal in size and where they are found unequal in size.
10. Distinguish anaphase of mitosis from anaphase I of meiosis.
11. List the main differences between mitosis and meiosis.
12. What is the significance of meiosis?
13. Discuss with your teacher about
    (i) haploid insects and lower plants where cell-division occurs, and
    (ii) some haploid cells in higher plants where cell-division does not occur.
14. Can there be mitosis without DNA replication in 'S' phase?
15. Can there be DNA replication without cell division?
16. Analyse the events during every stage of cell cycle and notice how the following two parameters change
    (i) number of chromosomes (N) per cell
    (ii) amount of DNA content (C) per cell

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UNIT 4

PLANT PHYSIOLOGY

Chapter 11
Photosynthesis in Higher Plants

Chapter 12
Respiration in Plants

Chapter 13
Plant Growth and Development

The description of structure and variation of living organisms over a period of time, ended up as two, apparently irreconcilable perspectives on biology. The two perspectives essentially rested on two levels of organisation of life forms and phenomena. One described at organismic and above level of organisation while the second described at cellular and molecular level of organisation. The first resulted in ecology and related disciplines. The second resulted in physiology and biochemistry. Description of physiological processes, in flowering plants as an example, is what is given in the chapters in this unit. The processes of photosynthesis, respiration and ultimately plant growth and development are described in molecular terms but in the context of cellular activities and even at organism level. Wherever appropriate, the relation of the physiological processes to environment is also discussed.

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Melvin Calvin

MELVIN CALVIN born in Minnesota in April, 1911, received his Ph.D. in Chemistry from the University of Minnesota. He served as Professor of Chemistry at the University of California, Berkeley.

Just after world war II, when the world was under shock after the Hiroshima-Nagasaki bombings, and seeing the ill-effects of radio-activity, Calvin and co-workers put radio-activity to beneficial use. He along with J.A. Bassham studied reactions in green plants forming sugar and other substances from raw materials like carbon dioxide, water and minerals by labelling the carbon dioxide with C^{14}. Calvin proposed that plants change light energy to chemical energy by transferring an electron in an organised array of pigment molecules and other substances. The mapping of the pathway of carbon assimilation in photosynthesis earned him Nobel Prize in 1961.

The principles of photosynthesis as established by Calvin are, at present, being used in studies on renewable resource for energy and materials and basic studies in solar energy research.

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Chapter 11
Photosynthesis in Higher Plants

11.1 What do we Know?

11.2 Early Experiments

11.3 Where does Photosynthesis take place?

11.4 How many Pigments are involved in Photosynthesis?

11.5 What is Light Reaction?

11.6 The Electron Transport

11.7 Where are the ATP and NADPH Used?

11.8 The C_4 Pathway

11.9 Photorespiration

11.10 Factors affecting Photosynthesis

All animals including human beings depend on plants for their food. Have you ever wondered from where plants get their food? Green plants, in fact, have to make or rather synthesise the food they need and all other organisms depend on them for their needs. The green plants make or rather synthesise the food they need through photosynthesis and are therefore called autotrophs. You have already learnt that the autotrophic nutrition is found only in plants and all other organisms that depend on the green plants for food are heterotrophs. Green plants carry out 'photosynthesis', a physico-chemical process by which they use light energy to drive the synthesis of organic compounds. Ultimately, all living forms on earth depend on sunlight for energy. The use of energy from sunlight by plants doing photosynthesis is the basis of life on earth. Photosynthesis is important due to two reasons: it is the primary source of all food on earth. It is also responsible for the release of oxygen into the atmosphere by green plants. *Have you ever thought what would happen if there were no oxygen to breath?* This chapter focusses on the structure of the photosynthetic machinery and the various reactions that transform light energy into chemical energy.

11.1 What do we Know?

Let us try to find out what we already know about photosynthesis. Some simple experiments you may have done in the earlier classes have shown that chlorophyll (green pigment of the leaf), light and CO_2 are required for photosynthesis to occur.

You may have carried out the experiment to look for starch formation in two leaves – a variegated leaf or a leaf that was partially covered with black paper, and exposed to light. On testing these leaves for the presence of starch it was clear that photosynthesis occurred only in the green parts of the leaves in the presence of light.

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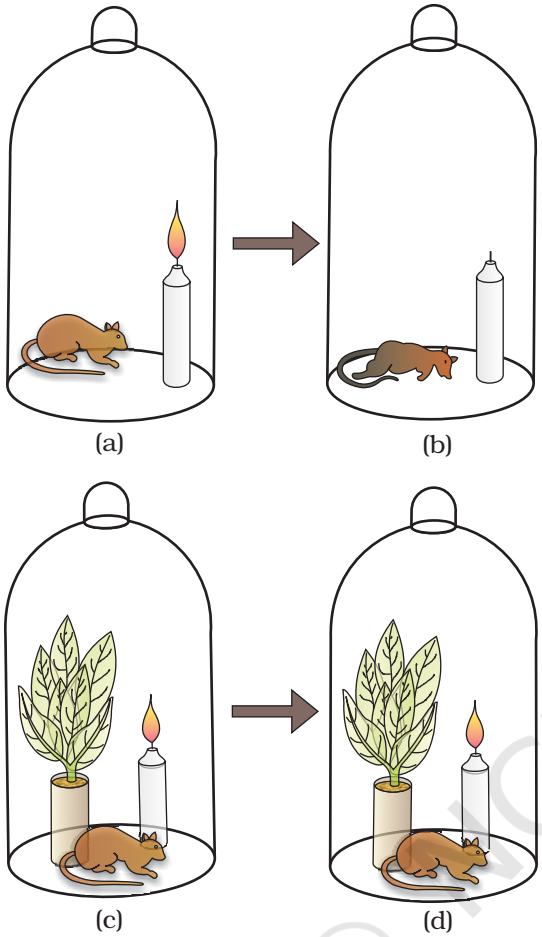

Figure 11.1 Priestley's experiment

Another experiment you may have carried out where a part of a leaf is enclosed in a test tube containing some KOH soaked cotton (which absorbs CO_2), while the other half is exposed to air. The setup is then placed in light for some time. On testing for the presence of starch later in the two parts of the leaf, you must have found that the exposed part of the leaf tested positive for starch while the portion that was in the tube, tested negative. This showed that CO_2 was required for photosynthesis. *Can you explain how this conclusion could be drawn?*

11.2 Early Experiments

It is interesting to learn about those simple experiments that led to a gradual development in our understanding of photosynthesis.

Joseph Priestley (1733-1804) in 1770 performed a series of experiments that revealed the essential role of air in the growth of green plants. Priestley, you may recall, discovered oxygen in 1774. Priestley observed that a candle burning in a closed space – a bell jar, soon gets extinguished (Figure 11.1 a, b, c, d). Similarly, a mouse would soon suffocate in a closed space. He concluded that a burning candle or an animal that breathe the air, both somehow, damage the air. But when he placed a mint plant in the same bell jar, he found that the mouse stayed alive and the candle continued to burn. Priestley hypothesised as follows: Plants restore to the air whatever breathing animals and burning candles remove.

Can you imagine how Priestley would have conducted the experiment using a candle and a plant? Remember, he would need to rekindle the candle to test whether it burns after a few days. *How many different ways can you think of to light the candle without disturbing the set-up?*

Using a similar setup as the one used by Priestley, but by placing it once in the dark and once in the sunlight, Jan Ingenhousz (1730-1799) showed that sunlight is essential for the plant process that somehow purifies the air fouled by burning candles or breathing animals. Ingenhousz in an elegant experiment with an aquatic plant showed that in bright sunlight, small bubbles were formed around the green parts while in the dark they did not. Later he identified these bubbles to be of oxygen. Hence he showed that it is only the green part of the plants that could release oxygen.

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It was not until about 1854 that Julius von Sachs provided evidence for production of glucose when plants grow. Glucose is usually stored as starch. His later studies showed that the green substance in plants (chlorophyll as we know it now) is located in special bodies (later called chloroplasts) within plant cells. He found that the green parts in plants is where glucose is made, and that the glucose is usually stored as starch.

Now consider the interesting experiments done by T.W Engelmann (1843 – 1909). Using a prism he split light into its spectral components and then illuminated a green alga, *Cladophora*, placed in a suspension of aerobic bacteria. The bacteria were used to detect the sites of O_2 evolution. He observed that the bacteria accumulated mainly in the region of blue and red light of the split spectrum. A first action spectrum of photosynthesis was thus described. It resembles roughly the absorption spectra of chlorophyll *a* and *b* (discussed in section 11.4).

By the middle of the nineteenth century the key features of plant photosynthesis were known, namely, that plants could use light energy to make carbohydrates from CO_2 and water. The empirical equation representing the total process of photosynthesis for oxygen evolving organisms was then understood as:

$$CO_2 + H_2O \xrightarrow{\text{Light}} [CH_2O] + O_2$$

where $[CH_2O]$ represented a carbohydrate (e.g., glucose, a six-carbon sugar).

A milestone contribution to the understanding of photosynthesis was that made by a microbiologist, Cornelius van Niel (1897-1985), who, based on his studies of purple and green bacteria, demonstrated that photosynthesis is essentially a light-dependent reaction in which hydrogen from a suitable oxidisable compound reduces carbon dioxide to carbohydrates. This can be expressed by:

$$2H_2A + CO_2 \xrightarrow{\text{Light}} 2A + CH_2O + H_2O$$

In green plants H_2O is the hydrogen donor and is oxidised to O_2. Some organisms do not release O_2 during photosynthesis. When H_2S, instead is the hydrogen donor for purple and green sulphur bacteria, the 'oxidation' product is sulphur or sulphate depending on the organism and not O_2. Hence, he inferred that the O_2 evolved by the green plant comes from H_2O, not from carbon dioxide. This was later proved by using radioisotopic techniques. The correct equation, that would represent the overall process of photosynthesis is therefore:

$$6CO_2 + 12H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6H_2O + 6O_2$$

where $C_6H_{12}O_6$ represents glucose. The O_2 released is from water; this was proved using radio isotope techniques. Note that this is not a single

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reaction but description of a multistep process called photosynthesis. *Can you explain why twelve molecules of water as substrate are used in the equation given above?*

11.3 WHERE DOES PHOTOSYNTHESIS TAKE PLACE?

You would of course answer: in 'the green leaf' or 'in the chloroplasts', based on what you earlier read in Chapter 8. You are definitely right. Photosynthesis does take place in the green leaves of plants but it does so also in other green parts of the plants. *Can you name some other parts where you think photosynthesis may occur?*

You would recollect from previous unit that the mesophyll cells in the leaves, have a large number of chloroplasts. Usually the chloroplasts align themselves along the walls of the mesophyll cells, such that they get the optimum quantity of the incident light. *When do you think the chloroplasts will be aligned with their flat surfaces parallel to the walls? When would they be perpendicular to the incident light?*

You have studied the structure of chloroplast in Chapter 8. Within the chloroplast there is membranous system consisting of grana, the stroma lamellae, and the matrix stroma (Figure 11.2). There is a clear division of labour within the chloroplast. The membrane system is responsible for trapping the light energy and also for the synthesis of ATP and NADPH. In stroma, enzymatic reactions synthesise sugar, which in turn forms starch. The former set of reactions, since they are directly light driven are called **light reactions** (photochemical reactions). The latter are not directly light driven but are dependent on the products of light reactions (ATP and NADPH). Hence, to distinguish the latter they are called, by convention, as **dark reactions** (carbon reactions). However, this should not be construed to mean that they occur in darkness or that they are not light-dependent.

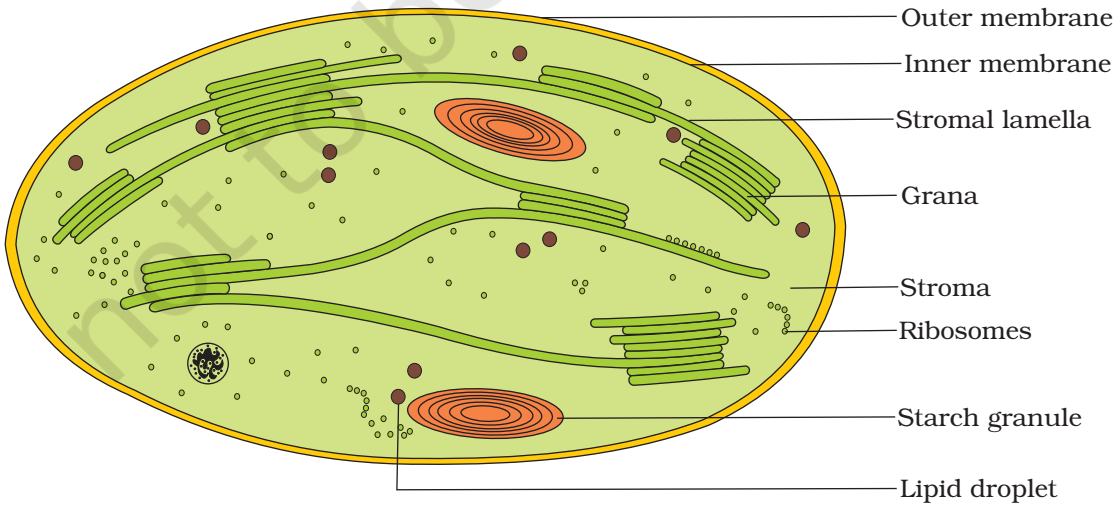

Figure 11.2 Diagrammatic representation of an electron micrograph of a section of chloroplast

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11.4 HOW MANY TYPES OF PIGMENTS ARE INVOLVED IN PHOTOSYNTHESIS?

Looking at plants have you ever wondered why and how there are so many shades of green in their leaves – even in the same plant? We can look for an answer to this question by trying to separate the leaf pigments of any green plant through paper chromatography. A chromatographic separation of the leaf pigments shows that the colour that we see in leaves is not due to a single pigment but due to four pigments: **Chlorophyll *a*** (bright or blue green in the chromatogram), **chlorophyll *b*** (yellow green), **xanthophylls** (yellow) and **carotenoids** (yellow to yellow-orange). Let us now see what roles various pigments play in photosynthesis.

Pigments are substances that have an ability to absorb light, at specific wavelengths. *Can you guess which is the most abundant plant pigment in the world?* Let us study the graph showing the ability of chlorophyll *a* pigment to absorb lights of different wavelengths (Figure 11.3 a). Of course, you are familiar with the wavelength of the visible spectrum of light as well as the VIBGYOR.

From Figure 11.3a can you determine the wavelength (colour of light) at which chlorophyll a shows the maximum absorption? Does it show another absorption peak at any other wavelengths too? If yes, which one?

Now look at Figure 11.3b showing the wavelengths at which maximum photosynthesis occurs in a plant. Can you see that the wavelengths at which there is maximum absorption by chlorophyll *a*, i.e., in the blue and the red regions, also shows higher rate of photosynthesis. Hence, we can conclude that chlorophyll *a* is the chief pigment associated with photosynthesis. *But by looking at Figure 11.3c can you say that there is a complete one-to-one overlap between the absorption spectrum of chlorophyll a and the action spectrum of photosynthesis?*

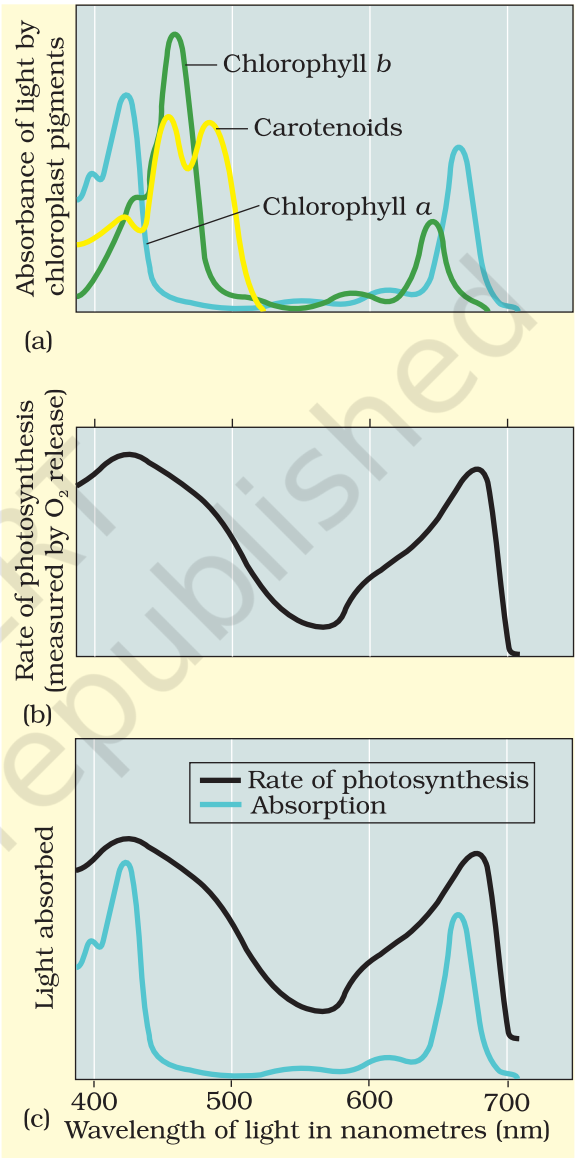

Figure 11.3a Graph showing the absorption spectrum of chlorophyll *a*, *b* and the carotenoids

Figure 11.3b Graph showing action spectrum of photosynthesis

Figure 11.3c Graph showing action spectrum of photosynthesis superimposed on absorption spectrum of chlorophyll *a*

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These graphs, together, show that most of the photosynthesis takes place in the blue and red regions of the spectrum; some photosynthesis does take place at the other wavelengths of the visible spectrum. Let us see how this happens. Though chlorophyll is the major pigment responsible for trapping light, other thylakoid pigments like chlorophyll *b*, xanthophylls and carotenoids, which are called accessory pigments, also absorb light and transfer the energy to chlorophyll *a*. Indeed, they not only enable a wider range of wavelength of incoming light to be utilised for photosyntesis but also protect chlorophyll *a* from photo-oxidation.

11.5 What is Light Reaction?

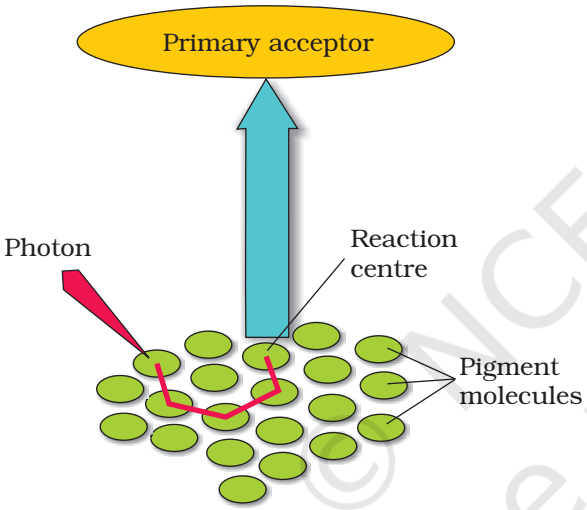

Figure 11.4 The light harvesting complex

Light reactions or the 'Photochemical' phase include light absorption, water splitting, oxygen release, and the formation of high-energy chemical intermediates, ATP and NADPH. Several protein complexes are involved in the process. The pigments are organised into two discrete photochemical **light harvesting complexes** (**LHC**) within the **Photosystem I (PS I)** and **Photosystem II (PS II)**. These are named in the sequence of their discovery, and not in the sequence in which they function during the light reaction. The LHC are made up of hundreds of pigment molecules bound to proteins. Each photosystem has all the pigments (except one molecule of chlorophyll *a*) forming a light harvesting system also called **antennae** (Figure 11.4). These pigments help to make photosynthesis more efficient by absorbing different wavelengths of light. The single chlorophyll *a* molecule forms the **reaction centre.** The reaction centre is different in both the photosystems. In PS I the reaction centre chlorophyll *a* has an absorption peak at 700 nm, hence is called **P700,** while in PS II it has absorption maxima at 680 nm, and is called **P680**.

11.6 The Electron Transport

In photosystem II the reaction centre chlorophyll *a* absorbs 680 nm wavelength of red light causing electrons to become excited and jump into an orbit farther from the atomic nucleus. These electrons are picked up by an electron acceptor which passes them to an **electrons transport**

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system consisting of cytochromes (Figure 11.5). This movement of electrons is downhill, in terms of an oxidation-reduction or redox potential scale. The electrons are not used up as they pass through the electron transport chain, but are passed on to the pigments of photosystem PS I. Simultaneously, electrons in the reaction centre of PS I are also excited when they receive red light of wavelength 700 nm and are transferred to another accepter molecule that has a greater redox potential. These electrons then are moved downhill again, this time to a molecule of energy-rich $NADP^+$. The addition of these electrons reduces $NADP^+$ to NADPH + H^+. This whole scheme of transfer of electrons, starting from the PS II, uphill to the acceptor, down the electron transport chain to PS I, excitation of electrons, transfer to another acceptor, and finally down hill to $NADP^+$ reducing it to NADPH + H^+ is called the **Z scheme**, due to its characterstic shape (Figure 11.5). This shape is formed when all the carriers are placed in a sequence on a redox potential scale.

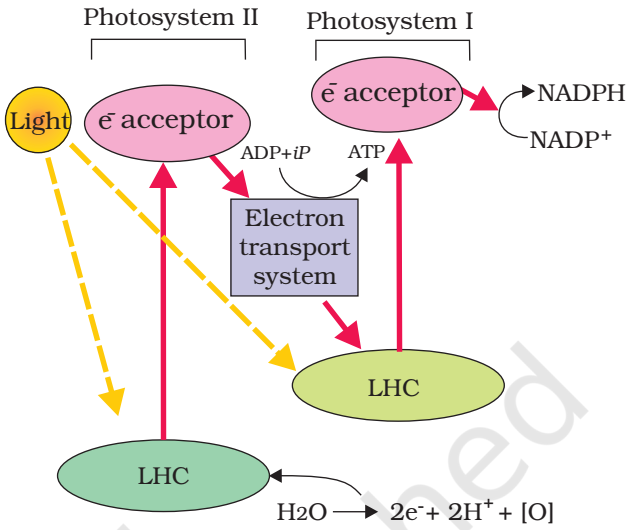

Figure 11.5 Z scheme of light reaction

11.6.1 Splitting of Water

You would then ask, *How does PS II supply electrons continuously?* The electrons that were moved from photosystem II must be replaced. This is achieved by electrons available due to splitting of water. The splitting of water is associated with the PS II; water is split into $2H^+$, [O] and electrons. This creates oxygen, one of the net products of photosynthesis. The electrons needed to replace those removed from photosystem I are provided by photosystem II.

$$2H_2O \longrightarrow 4H^+ + O_2 + 4e^-$$

We need to emphasise here that the water splitting complex is associated with the PS II, which itself is physically located on the inner side of the membrane of the thylakoid. *Then, where are the protons and O_2 formed likely to be released – in the lumen? or on the outer side of the membrane?*

11.6.2 Cyclic and Non-cyclic Photo-phosphorylation

Living organisms have the capability of extracting energy from oxidisable substances and store this in the form of bond energy. Special substances like ATP, carry this energy in their chemical bonds. The process through which

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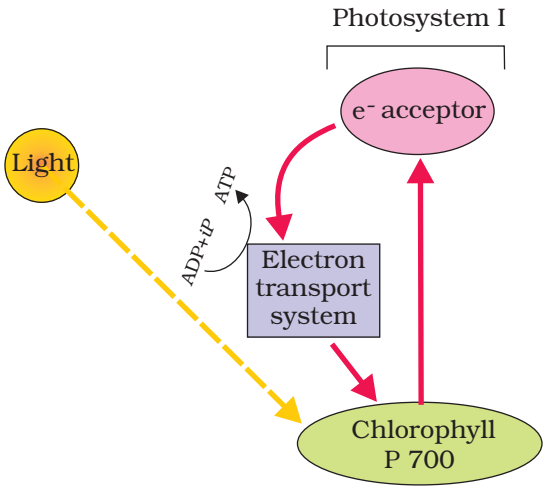

Figure 11.6 Cyclic photophosphorylation

ATP is synthesised by cells (in mitochondria and chloroplasts) is named phosphorylation. Photo-phosphorylation is the synthesis of ATP from ADP and inorganic phosphate in the presence of light. When the two photosystems work in a series, first PS II and then the PS I, a process called non-cyclic photo-phosphorylation occurs. The two photosystems are connected through an electron transport chain, as seen earlier – in the Z scheme. Both ATP and NADPH + H^+ are synthesised by this kind of electron flow (Figure 11.5).

When only PS I is functional, the electron is circulated within the photosystem and the phosphorylation occurs due to cyclic flow of electrons (Figure 11.6). A possible location where this could be happening is in the stroma lamellae. While the membrane or lamellae of the grana have both PS I and PS II the stroma lamellae membranes lack PS II as well as NADP reductase enzyme. The excited electron does not pass on to $NADP^+$ but is cycled back to the PS I complex through the electron transport chain (Figure 11.6). The cyclic flow hence, results only in the synthesis of ATP, but not of NADPH + H^+. Cyclic photophosphorylation also occurs when only light of wavelengths beyond 680 nm are available for excitation.

11.6.3 Chemiosmotic Hypothesis

Let us now try and understand how actually ATP is synthesised in the chloroplast. The chemiosmotic hypothesis has been put forward to explain the mechanism. Like in respiration, in photosynthesis too, ATP synthesis is linked to development of a proton gradient across a membrane. This time these are the membranes of thylakoid. There is one difference though, here the proton accumulation is towards the inside of the membrane, i.e., in the lumen. In respiration, protons accumulate in the intermembrane space of the mitochondria when electrons move through the ETS (Chapter 12).

Let us understand what causes the proton gradient across the membrane. We need to consider again the processes that take place during the activation of electrons and their transport to determine the steps that cause a proton gradient to develop (Figure 11.7).

(a) Since splitting of the water molecule takes place on the inner side of the membrane, the protons or hydrogen ions that are produced by the splitting of water accumulate within the lumen of the thylakoids.

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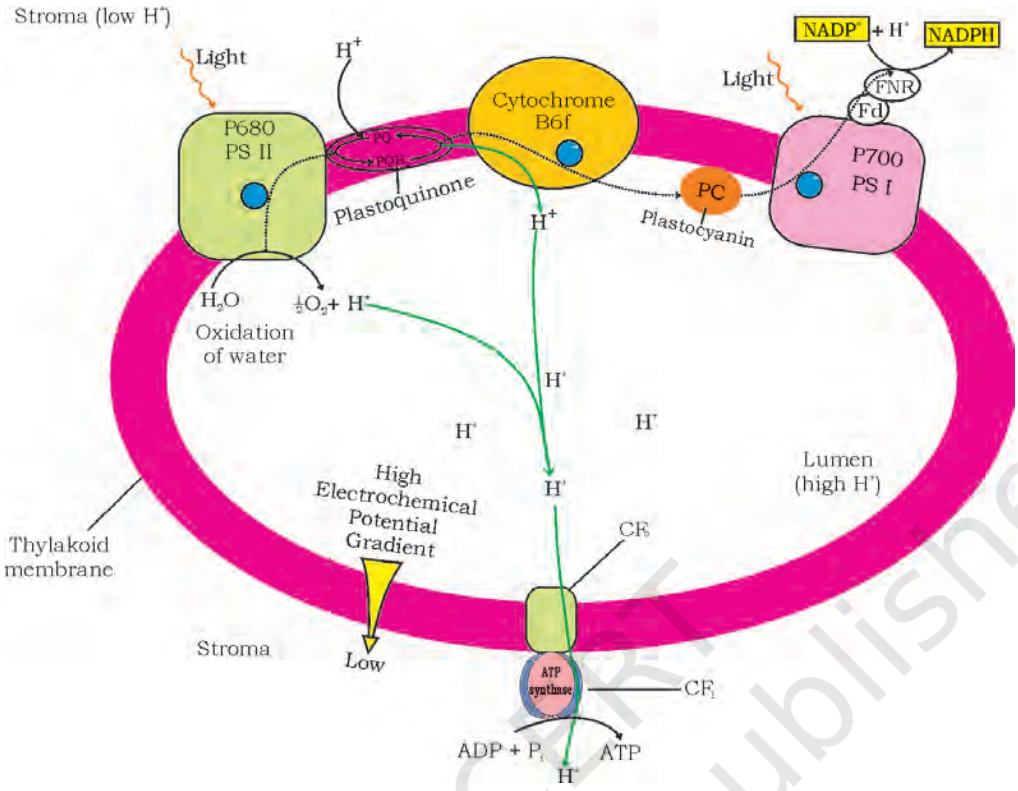

Figure 11.7 ATP synthesis through chemiosmosis

(b) As electrons move through the photosystems, protons are transported across the membrane. This happens because the primary accepter of electron which is located towards the outer side of the membrane transfers its electron not to an electron carrier but to an H carrier. Hence, this molecule removes a proton from the stroma while transporting an electron. When this molecule passes on its electron to the electron carrier on the inner side of the membrane, the proton is released into the inner side or the lumen side of the membrane.

(c) The NADP reductase enzyme is located on the stroma side of the membrane. Along with electrons that come from the acceptor of electrons of PS I, protons are necessary for the reduction of $NADP^+$ to NADPH+ H^+. These protons are also removed from the stroma.

Hence, within the chloroplast, protons in the stroma decrease in number, while in the lumen there is accumulation of protons. This creates a proton gradient across the thylakoid membrane as well as a measurable decrease in pH in the lumen.

Why are we so interested in the proton gradient? This gradient is important because it is the breakdown of this gradient that leads to the synthesis of ATP. The gradient is broken down due to the movement of protons across the membrane to the stroma through the transmembrane

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channel of the CF_0 of the ATP synthase. The ATP synthase enzyme consists of two parts: one called the CF_0 is embedded in the thylakoid membrane and forms a transmembrane channel that carries out facilitated diffusion of protons across the membrane. The other portion is called CF_1 and protrudes on the outer surface of the thylakoid membrane on the side that faces the stroma. The break down of the gradient provides enough energy to cause a conformational change in the CF_1 particle of the ATP synthase, which makes the enzyme synthesise several molecules of energy-packed ATP.

Chemiosmosis requires a membrane, a proton pump, a proton gradient and ATP synthase. Energy is used to pump protons across a membrane, to create a gradient or a high concentration of protons within the thylakoid lumen. ATP synthase has a channel that allows diffusion of protons back across the membrane; this releases enough energy to activate ATP synthase enzyme that catalyses the formation of ATP.

Along with the NADPH produced by the movement of electrons, the ATP will be used immediately in the biosynthetic reaction taking place in the stroma, responsible for fixing CO_2, and synthesis of sugars.

11.7 WHERE ARE THE ATP AND NADPH USED?

We learnt that the products of light reaction are ATP, NADPH and O_2. Of these O_2 diffuses out of the chloroplast while ATP and NADPH are used to drive the processes leading to the synthesis of food, more accurately, sugars. This is the **biosynthetic phase** of photosynthesis. This process does not directly depend on the presence of light but is dependent on the products of the light reaction, i.e., ATP and NADPH, besides CO_2 and H_2O. You may wonder how this could be verified; it is simple: immediately after light becomes unavailable, the biosynthetic process continues for some time, and then stops. If then, light is made available, the synthesis starts again.

Can we, hence, say that calling the biosynthetic phase as the ***dark reaction*** *is a misnomer? Discuss this amongst yourselves.*

Let us now see how the ATP and NADPH are used in the biosynthetic phase. We saw earlier that CO_2 is combined with H_2O to produce $(CH_2O)_n$ or sugars. It was of interest to scientists to find out how this reaction proceeded, or rather what was the first product formed when CO_2 is taken into a reaction or fixed. Just after world war II, among the several efforts to put radioisotopes to beneficial use, the work of Melvin Calvin is exemplary. The use of radioactive ^{14}C by him in algal photosynthesis studies led to the discovery that the first CO_2 fixation product was a 3-carbon organic acid. He also contributed to working out the complete biosynthetic pathway; hence it was called **Calvin cycle** after him. The first product identified was **3-phosphoglyceric** acid or in short **PGA**. *How many carbon atoms does it have?*

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Scientists also tried to know whether all plants have PGA as the first product of CO_2 fixation, or whether any other product was formed in other plants. Experiments conducted over a wide range of plants led to the discovery of another group of plants, where the first stable product of CO_2 fixation was again an organic acid, but one which had 4 carbon atoms in it. This acid was identified to be **oxaloacetic acid** or OAA. Since then CO_2 assimilation during photosynthesis was said to be of two main types: those plants in which the first product of CO_2 fixation is a C_3 acid (PGA), i.e., the **C_3 pathway,** and those in which the first product was a C_4 acid (OAA), i.e., the **C_4 pathway**. These two groups of plants showed other associated characteristics that we will discuss later.

11.7.1 The Primary Acceptor of CO_2

Let us now ask ourselves a question that was asked by the scientists who were struggling to understand the 'dark reaction'. *How many carbon atoms would a molecule have which after accepting (fixing) CO_2, would have 3 carbons (of PGA)?*

The studies very unexpectedly showed that the acceptor molecule was a 5-carbon ketose sugar – ribulose bisphosphate (RuBP). *Did any of you think of this possibility?* Do not worry; the scientists also took a long time and conducted many experiments to reach this conclusion. They also believed that since the first product was a C_3 acid, the primary acceptor would be a 2-carbon compound; they spent many years trying to identify a 2-carbon compound before they discovered the 5-carbon RuBP.

11.7.2 The Calvin Cycle

Calvin and his co-workers then worked out the whole pathway and showed that the pathway operated in a cyclic manner; the RuBP was regenerated. Let us now see how the Calvin pathway operates and where the sugar is synthesised. Let us at the outset understand very clearly that the Calvin pathway occurs in **all photosynthetic plants**; it does not matter whether they have C_3 or C_4 (or any other) pathways (Figure 11.8).

For ease of understanding, the Calvin cycle can be described under three stages: carboxylation, reduction and regeneration.

1. **Carboxylation** – Carboxylation is the fixation of CO_2 into a stable organic intermediate. Carboxylation is the most crucial step of the Calvin cycle where CO_2 is utilised for the carboxylation of RuBP. This reaction is catalysed by the enzyme RuBP carboxylase which results in the formation of two molecules of 3-PGA. Since this enzyme also has an oxygenation activity it would be more correct to call it RuBP carboxylase-oxygenase or **RuBisCO**.

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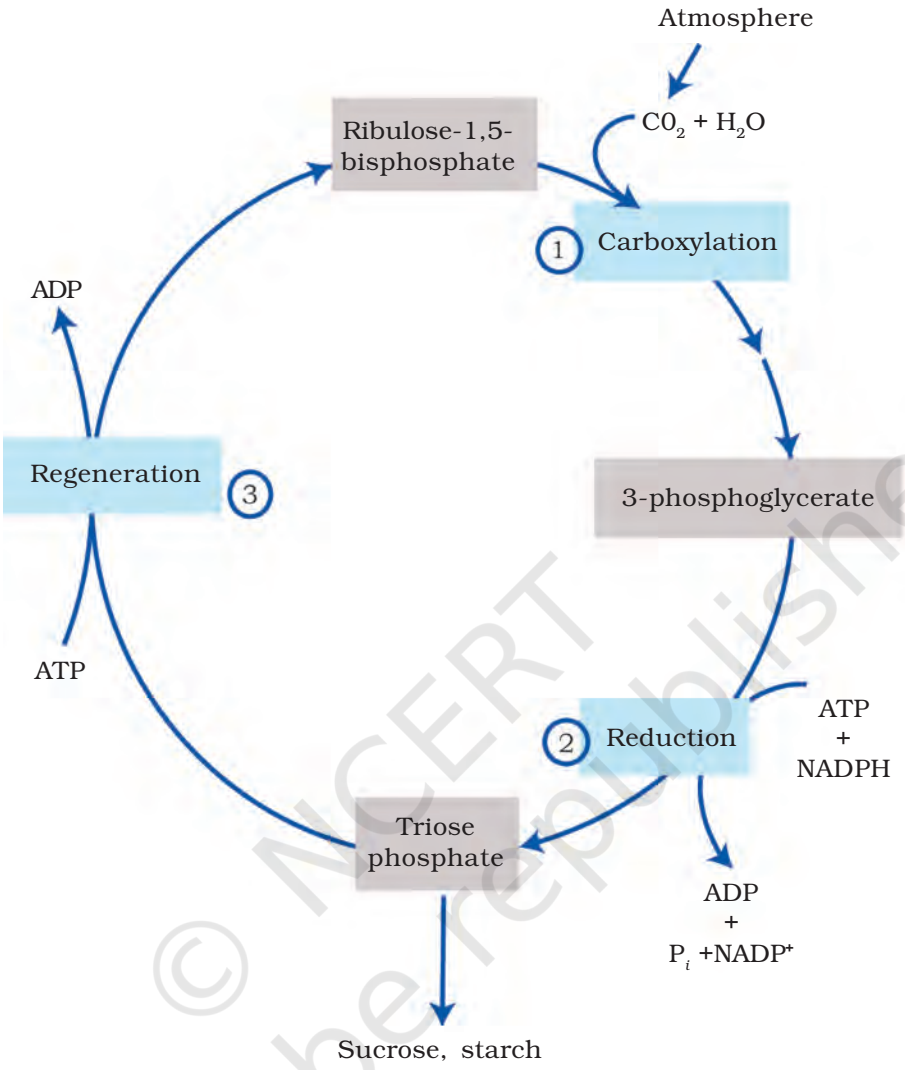

Figure 11.8 The Calvin cycle proceeds in three stages : (1) carboxylation, during which CO_2 combines with ribulose-1,5-bisphosphate; (2) reduction, during which carbohydrate is formed at the expense of the photochemically made ATP and NADPH; and (3) regeneration during which the CO_2 acceptor ribulose-1,5-bisphosphate is formed again so that the cycle continues

2. **Reduction** – These are a series of reactions that lead to the formation of glucose. The steps involve utilisation of 2 molecules of ATP for phosphorylation and two of NADPH for reduction per CO_2 molecule fixed. The fixation of six molecules of CO_2 and 6 turns of the cycle are required for the formation of one molecule of glucose from the pathway.

3. **Regeneration** – Regeneration of the CO_2 acceptor molecule RuBP is crucial if the cycle is to continue uninterrupted. The regeneration steps require one ATP for phosphorylation to form RuBP.

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Hence for every CO_2 molecule entering the Calvin cycle, 3 molecules of ATP and 2 of NADPH are required. It is probably to meet this difference in number of ATP and NADPH used in the dark reaction that the cyclic phosphorylation takes place.

To make one molecule of glucose 6 turns of the cycle are required. *Work out how many ATP and NADPH molecules will be required to make one molecule of glucose through the Calvin pathway.*

It might help you to understand all of this if we look at what goes in and what comes out of the Calvin cycle.

In	Out
Six CO_2	One glucose
18 ATP	18 ADP
12 NADPH	12 NADP

11.8 THE C_4 PATHWAY

Plants that are adapted to dry tropical regions have the C_4 pathway mentioned earlier. Though these plants have the C_4 oxaloacetic acid as the first CO_2 fixation product they use the C_3 pathway or the Calvin cycle as the main biosynthetic pathway. Then, in what way are they different from C_3 plants? This is a question that you may reasonably ask.

C_4 plants are special: They have a special type of leaf anatomy, they tolerate higher temperatures, they show a response to high light intensities, they lack a process called photorespiration and have greater productivity of biomass. Let us understand these one by one.

Study vertical sections of leaves, one of a C_3 plant and the other of a C_4 plant. *Do you notice the differences? Do both have the same types of mesophylls? Do they have similar cells around the vascular bundle sheath?*

The particularly large cells around the vascular bundles of the C_4 plants are called **bundle sheath cells**, and the leaves which have such anatomy are said to have **'Kranz' anatomy**. 'Kranz' means 'wreath' and is a reflection of the arrangement of cells. The bundle sheath cells may form **several layers** around the vascular bundles; they are characterised by having a large number of chloroplasts, thick walls impervious to gaseous exchange and no intercellular spaces. You may like to cut a section of the leaves of C_4 plants – maize or sorghum – to observe the Kranz anatomy and the distribution of mesophyll cells.

It would be interesting for you to collect leaves of diverse species of plants around you and cut vertical sections of the leaves. Observe under the microscope – look for the bundle sheath around the vascular bundles. The presence of the bundle sheath would help you identify the C_4 plants.

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Now study the pathway shown in Figure 11.9. This pathway that has been named the Hatch and Slack Pathway, is again a cyclic process. Let us study the pathway by listing the steps.

The primary CO_2 acceptor is a 3-carbon molecule **phosphoenol pyruvate (PEP)** and is present in the mesophyll cells. The enzyme responsible for this fixation is **PEP carboxylase** or PEPcase. It is important to register that the mesophyll cells lack RuBisCO enzyme. The C_4 acid OAA is formed in the mesophyll cells.

It then forms other 4-carbon compounds like malic acid or aspartic acid in the mesophyll cells itself, which are transported to the bundle sheath cells. In the bundle sheath cells these C_4 acids are broken down to release CO_2 and a 3-carbon molecule.

The 3-carbon molecule is transported back to the mesophyll where it is converted to PEP again, thus, completing the cycle.

The CO_2 released in the bundle sheath cells enters the C_3 or the Calvin pathway, a pathway common to all plants. The bundle sheath cells are

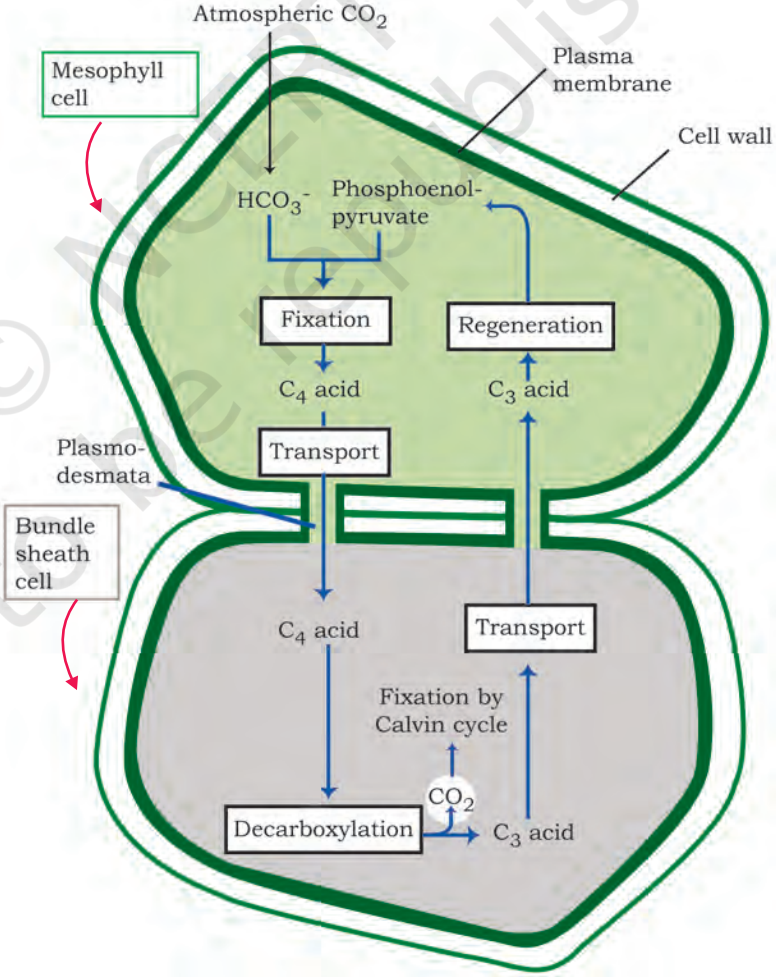

Figure 11.9 Diagrammatic representation of the Hatch and Slack Pathway

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rich in an enzyme Ribulose bisphosphate carboxylase-oxygenase **(RuBisCO)**, but lack PEPcase. Thus, the basic pathway that results in the formation of the sugars, the Calvin pathway, is common to the C_3 and C_4 plants.

Did you note that the Calvin pathway occurs in all the mesophyll cells of the C_3 plants? In the C_4 plants it does not take place in the mesophyll cells but does so only in the bundle sheath cells.

11.9 PHOTORESPIRATION

Let us try and understand one more process that creates an important difference between C_3 and C_4 plants – **Photorespiration**. To understand photorespiration we have to know a little bit more about the first step of the Calvin pathway – the first CO_2 fixation step. This is the reaction where RuBP combines with CO_2 to form 2 molecules of 3PGA, that is catalysed by RuBisCO.

$$RuBP + CO_2 \xrightarrow{RuBisCo} 2 \times 3PGA$$

RuBisCO that is the most abundant enzyme in the world (Do you wonder why?) is characterised by the fact that its active site can bind to both CO_2 and O_2 – hence the name. *Can you think how this could be possible?* RuBisCO has a much greater affinity for CO_2 when the CO_2: O_2 is nearly equal. Imagine what would happen if this were not so! This binding is competitive. It is the relative concentration of O_2 and CO_2 that determines which of the two will bind to the enzyme.

In C_3 plants some O_2 does bind to RuBisCO, and hence CO_2 fixation is decreased. Here the RuBP instead of being converted to 2 molecules of PGA binds with O_2 to form one molecule of phosphoglycerate and phosphoglycolate (2 Carbon) in a pathway called photorespiration. In the photorespiratory pathway, there is neither synthesis of sugars, nor of ATP. Rather it results in the release of CO_2 with the utilisation of ATP. In the photorespiratory pathway there is no synthesis of ATP or NADPH. The biological function of photorespiration is not known yet.

In C_4 plants photorespiration does not occur. This is because they have a mechanism that increases the concentration of CO_2 at the enzyme site. This takes place when the C_4 acid from the mesophyll is broken down in the bundle sheath cells to release CO_2 – this results in increasing the intracellular concentration of CO_2. In turn, this ensures that the RuBisCO functions as a carboxylase minimising the oxygenase activity.

Now that you know that the C_4 plants lack photorespiration, you probably can understand why productivity and yields are better in these plants. In addition, these plants show tolerance to higher temperatures.

Based on the above discussion can you compare plants showing the C_3 and the C_4 pathway? Use the table format given in table 11.1 and fill in the information.

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TABLE 11.1 Fill in the Columns 2 and 3 in this table to highlight the differences between C_3 and C_4 Plants

Characteristics	C_3 Plants	C_4 Plants	Choose from
Cell type in which the Calvin cycle takes place			Mesophyll/Bundle sheath/both
Cell type in which the initial carboxylation reaction occurs			Mesophyll/Bundle sheath /both
How many cell types does the leaf have that fix CO_2.			Two: Bundle sheath and mesophyll One: Mesophyll Three: Bundle sheath, palisade, spongy mesophyll
Which is the primary CO_2 acceptor			RuBP/PEP/PGA
Number of carbons in the primary CO_2 acceptor			5 / 4 / 3
Which is the primary CO_2 fixation product			PGA/OAA/RuBP/PEP
No. of carbons in the primary CO_2 fixation product			3 / 4 / 5
Does the plant have RuBisCO?			Yes/No/Not always
Does the plant have PEP Case?			Yes/No/Not always
Which cells in the plant have Rubisco?			Mesophyll/Bundle sheath/none
CO_2 fixation rate under high light conditions			Low/ high/ medium
Whether photorespiration is present at low light intensities			High/negligible/sometimes
Whether photorespiration is present at high light intensities			High/negligible/sometimes
Whether photorespiration would be present at low CO_2 concentrations			High/negligible/sometimes
Whether photorespiration would be present at high CO_2 concentrations			High/negligible/sometimes
Temperature optimum			30-40°C/20-25°C/above 40°C
Examples			Cut vertical sections of leaves of different plants and observe under the microscope for Kranz anatomy and list them in the appropriate columns.

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11.10 FACTORS AFFECTING PHOTOSYNTHESIS

An understanding of the factors that affect photosynthesis is necessary. The rate of photosynthesis is very important in determining the yield of plants including crop plants. Photosynthesis is under the influence of several factors, both internal (plant) and external. The plant factors include the number, size, age and orientation of leaves, mesophyll cells and chloroplasts, internal CO_2 concentration and the amount of chlorophyll. The plant or internal factors are dependent on the genetic predisposition and the growth of the plant.

The external factors would include the availability of sunlight, temperature, CO_2 concentration and water. As a plant photosynthesises, all these factors will simultaneously affect its rate. Hence, though several factors interact and simultaneously affect photosynthesis or CO_2 fixation, usually one factor is the major cause or is the one that limits the rate. Hence, at any point the rate will be determined by the factor available at sub-optimal levels.

When several factors affect any [bio] chemical process, Blackman's (1905) **Law of Limiting Factors** comes into effect. This states the following:

If a chemical process is affected by more than one factor, then its rate will be determined by the factor which is nearest to its minimal value: it is the factor which directly affects the process if its quantity is changed.

For example, despite the presence of a green leaf and optimal light and CO_2 conditions, the plant may not photosynthesise if the temperature is very low. This leaf, if given the optimal temperature, will start photosynthesising.

11.10.1 Light

We need to distinguish between light quality, light intensity and the duration of exposure to light, while discussing light as a factor that affects photosynthesis. There is a linear relationship between incident light and CO_2 fixation rates at low light intensities. At higher light intensities, gradually the rate does not show further increase as other factors become limiting (Figure 11.10). What is interesting to note is that light saturation occurs at 10 per cent of the full sunlight. Hence, except for plants in shade or in dense forests, light is rarely a limiting factor in nature. Increase in

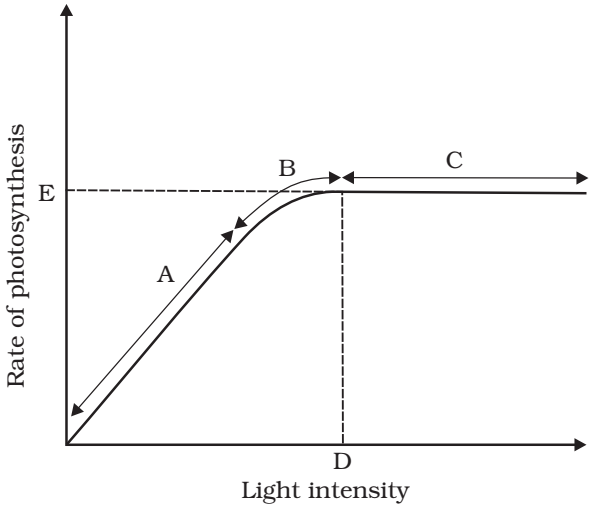

Figure 11.10 Graph of light intensity on the rate of photosynthesis

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incident light beyond a point causes the breakdown of chlorophyll and a decrease in photosynthesis.

11.10.2 Carbon dioxide Concentration

Carbon dioxide is the major limiting factor for photosynthesis. The concentration of CO_2 is very low in the atmosphere (between 0.03 and 0.04 per cent). Increase in concentration upto 0.05 per cent can cause an increase in CO_2 fixation rates; beyond this the levels can become damaging over longer periods.

The C_3 and C_4 plants respond differently to CO_2 concentrations. At low light conditions neither group responds to high CO_2 conditions. At high light intensities, both C_3 and C_4 plants show increase in the rates of photosynthesis. What is important to note is that the C_4 plants show saturation at about 360 $\mu l L^{-1}$ while C_3 responds to increased CO_2 concentration and saturation is seen only beyond 450 $\mu l L^{-1}$. Thus, current availability of CO_2 levels is limiting to the C_3 plants.

The fact that C_3 plants respond to higher CO_2 concentration by showing increased rates of photosynthesis leading to higher productivity has been used for some greenhouse crops such as tomatoes and bell pepper. They are allowed to grow in carbon dioxide enriched atmosphere that leads to higher yields.

11.10.3 Temperature

The dark reactions being enzymatic are temperature controlled. Though the light reactions are also temperature sensitive they are affected to a much lesser extent. The C_4 plants respond to higher temperatures and show higher rate of photosynthesis while C_3 plants have a much lower temperature optimum.

The temperature optimum for photosynthesis of different plants also depends on the habitat that they are adapted to. Tropical plants have a higher temperature optimum than the plants adapted to temperate climates.

11.10.4 Water

Even though water is one of the reactants in the light reaction, the effect of water as a factor is more through its effect on the plant, rather than directly on photosynthesis. Water stress causes the stomata to close hence reducing the CO_2 availability. Besides, water stress also makes leaves wilt, thus, reducing the surface area of the leaves and their metabolic activity as well.

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SUMMARY

Green plants make their own food by photosynthesis. During this process carbon dioxide from the atmosphere is taken in by leaves through stomata and used for making carbohydrates, principally glucose and starch. Photosynthesis takes place only in the green parts of the plants, mainly the leaves. Within the leaves, the mesophyll cells have a large number of chloroplasts that are responsible for CO_2 fixation. Within the chloroplasts, the membranes are sites for the light reaction, while the chemosynthetic pathway occurs in the stroma. Photosynthesis has two stages: the light reaction and the carbon fixing reactions. In the light reaction the light energy is absorbed by the pigments present in the antenna, and funnelled to special chlorophyll *a* molecules called reaction centre chlorophylls. There are two photosystems, PS I and PS II. PS I has a 700 nm absorbing chlorophyll *a* P700 molecule at its reaction centre, while PS II has a P680 reaction centre that absorbs red light at 680 nm. After absorbing light, electrons are excited and transferred through PS II and PS I and finally to NAD forming NADH. During this process a proton gradient is created across the membrane of the thylakoid. The breakdown of the protons gradient due to movement through the F_0 part of the ATPase enzyme releases enough energy for synthesis of ATP. Splitting of water molecules is associated with PS II resulting in the release of O_2, protons and transfer of electrons to PS II.

In the carbon fixation cycle, CO_2 is added by the enzyme, RuBisCO, to a 5-carbon compound RuBP that is converted to 2 molecules of 3-carbon PGA. This is then converted to sugar by the Calvin cycle, and the RuBP is regenerated. During this process ATP and NADPH synthesised in the light reaction are utilised. RuBisCO also catalyses a wasteful oxygenation reaction in C_3 plants: photorespiration.

Some tropical plants show a special type of photosynthesis called C_4 pathway. In these plants the first product of CO_2 fixation that takes place in the mesophyll, is a 4-carbon compound. In the bundle sheath cells the Calvin pathway is carried out for the synthesis of carbohydrates.

EXERCISES

1. By looking at a plant externally, can you tell whether a plant is C_3 or C_4? Why and how?
2. By looking at which internal structure of a plant you can tell whether a plant is C_3 or C_4? Explain.
3. Even though a very few cells in a C_4 plant carry out the biosynthetic – Calvin pathway, yet they are highly productive. Can you discuss why?

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4. RuBisCO is an enzyme that acts both as a carboxylase and oxygenase. Why do you think RuBisCO carries out more carboxylation in C_4 plants?
5. Suppose there were plants that had a high concentration of Chlorophyll *b*, but lacked chlorophyll *a*, would it carry out photosynthesis? Then why do plants have chlorophyll *b* and other accessory pigments?
6. Why is the colour of a leaf kept in the dark frequently becomes yellow, or pale green? Which pigment do you think is more stable?
7. Look at leaves of the same plant on the shady side and compare it with the leaves on the sunny side. Or, compare the potted plants kept in the sunlight with those in the shade. Which of them has leaves that are darker green ? Why?
8. Figure 11.10 shows the effect of light on the rate of photosynthesis. Based on the graph, answer the following questions:

   (a) At which point/s (A, B or C) in the curve light is a limiting factor?
   (b) What could be the limiting factor/s in region A?
   (c) What do C and D represent on the curve?
9. Give comparison between the following:

   (a) C_3 and C_4 pathways
   (b) Cyclic and non-cyclic photophosphorylation
   (c) Anatomy of leaf in C_3 and C_4 plants

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Chapter 12
Respiration in Plants

12.1 Do Plants Breathe?

12.2 Glycolysis

12.3 Fermentation

12.4 Aerobic Respiration

12.5 The Respiratory Balance Sheet

12.6 Amphibolic Pathway

12.7 Respiratory Quotient

All of us breathe to live, but why is breathing so essential to life? What happens when we breathe? Also, do all living organisms, including plants and microbes, breathe? If so, how?

All living organisms need energy for carrying out daily life activities, be it absorption, transport, movement, reproduction or even breathing. Where does all this energy come from? We know we eat food for energy – but how is this energy taken from food? How is this energy utilised? Do all foods give the same amount of energy? Do plants 'eat'? Where do plants get their energy from? And micro-organisms – for their energy requirements, do they eat 'food'?

You may wonder at the several questions raised above – they may seem to be very disconnected. But in reality, the process of breathing is very much connected to the process of release of energy from food. Let us try and understand how this happens.

All the energy required for 'life' processes is obtained by oxidation of some macromolecules that we call 'food'. Green plants and cyanobacteria can prepare their own food; by the process of photosynthesis they trap light energy and convert it into chemical energy that is stored in the bonds of carbohydrates like glucose, sucrose and starch. We must remember that in green plants too, not all cells, tissues and organs photosynthesise; only cells containing chloroplasts, that are most often located in the superficial layers, carry out photosynthesis. Hence, even in green plants all other organs, tissues and cells that are non-green, need food for oxidation. Hence, food has to be translocated to all non-green parts. Animals are heterotrophic, i.e., they obtain food from plants

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directly (herbivores) or indirectly (carnivores). Saprophytes like fungi are dependent on dead and decaying matter. What is important to recognise is that ultimately all the food that is respired for life processes comes from photosynthesis. This chapter deals with **cellular respiration** or the mechanism of breakdown of food materials within the cell to release energy, and the trapping of this energy for synthesis of ATP.

Photosynthesis, of course, takes place within the chloroplasts (in the eukaryotes), whereas the breakdown of complex molecules to yield energy takes place in the cytoplasm and in the mitochondria (also only in eukaryotes). The breaking of the C-C bonds of complex compounds through oxidation within the cells, leading to release of considerable amount of energy is called **respiration**. The compounds that are oxidised during this process are known as **respiratory substrates.** Usually carbohydrates are oxidised to release energy, but proteins, fats and even organic acids can be used as respiratory substances in some plants, under certain conditions. During oxidation within a cell, all the energy contained in respiratory substrates is not released free into the cell, or in a single step. It is released in a series of slow step-wise reactions controlled by enzymes, and it is trapped as chemical energy in the form of ATP. Hence, it is important to understand that the energy released by oxidation in respiration is not (or rather cannot be) used directly but is used to synthesise ATP, which is broken down whenever (and wherever) energy needs to be utilised. Hence, ATP acts as the energy currency of the cell. This energy trapped in ATP is utilised in various energy-requiring processes of the organisms, and the carbon skeleton produced during respiration is used as precursors for biosynthesis of other molecules in the cell.

12.1 Do Plants Breathe?

Well, the answer to this question is not quite so direct. Yes, plants require O_2 for respiration to occur and they also give out CO_2. Hence, plants have systems in place that ensure the availability of O_2. Plants, unlike animals, have no specialised organs for gaseous exchange but they have stomata and lenticels for this purpose. There are several reasons why plants can get along without respiratory organs. First, each plant part takes care of its own gas-exchange needs. There is very little transport of gases from one plant part to another. Second, plants do not present great demands for gas exchange. Roots, stems and leaves respire at rates far lower than animals do. Only during photosynthesis are large volumes of gases exchanged and, each leaf is well adapted to take care of its own needs during these periods. When cells photosynthesise, availability of O_2 is not a problem in these cells since O_2 is released within the cell. Third, the

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distance that gases must diffuse even in large, bulky plants is not great. Each living cell in a plant is located quite close to the surface of the plant. 'This is true for leaves', you may ask, 'but what about thick, woody stems and roots?' In stems, the 'living' cells are organised in thin layers inside and beneath the bark. They also have openings called lenticels. The cells in the interior are dead and provide only mechanical support. Thus, most cells of a plant have at least a part of their surface in contact with air. This is also facilitated by the loose packing of parenchyma cells in leaves, stems and roots, which provide an interconnected network of air spaces.

The complete combustion of glucose, which produces CO_2 and H_2O as end products, yields energy most of which is given out as heat.

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

If this energy is to be useful to the cell, it should be able to utilise it to synthesise other molecules that the cell requires. The strategy that the plant cell uses is to catabolise the glucose molecule in such a way that not all the liberated energy goes out as heat. The key is to oxidise glucose not in one step but in several small steps enabling some steps to be just large enough such that the energy released can be coupled to ATP synthesis. How this is done is, essentially, the story of respiration.

During the process of respiration, oxygen is utilised, and carbon dioxide, water and energy are released as products. The combustion reaction requires oxygen. But some cells live where oxygen may or may not be available. *Can you think of such situations (and organisms) where O_2 is not available?* There are sufficient reasons to believe that the first cells on this planet lived in an atmosphere that lacked oxygen. Even among present-day living organisms, we know of several that are adapted to anaerobic conditions. Some of these organisms are facultative anaerobes, while in others the requirement for anaerobic condition is obligate. In any case, all living organisms retain the enzymatic machinery to partially oxidise glucose without the help of oxygen. This breakdown of glucose to pyruvic acid is called **glycolysis.**

12.2 GLYCOLYSIS

The term glycolysis has originated from the Greek words, *glycos* for sugar, and *lysis* for splitting. The scheme of glycolysis was given by Gustav Embden, Otto Meyerhof, and J. Parnas, and is often referred to as the EMP pathway. In anaerobic organisms, it is the only process in respiration. Glycolysis occurs in the cytoplasm of the cell and is present in all living organisms. In this process, glucose undergoes partial oxidation to form two molecules of pyruvic acid. In plants, this glucose is derived from sucrose, which is the end product of photosynthesis, or from storage

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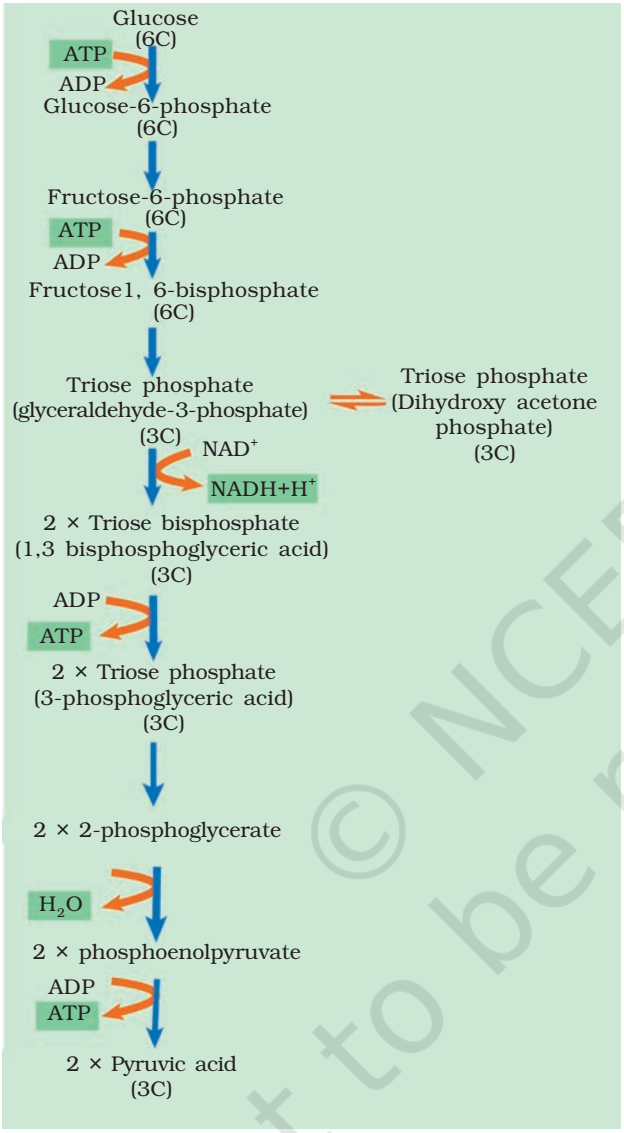

Figure 12.1 Steps of glycolysis

carbohydrates. Sucrose is converted into glucose and fructose by the enzyme, invertase, and these two monosaccharides readily enter the glycolytic pathway. Glucose and fructose are phosphorylated to give rise to glucose-6-phosphate by the activity of the enzyme hexokinase. This phosphorylated form of glucose then isomerises to produce fructose-6-phosphate. Subsequent steps of metabolism of glucose and fructose are same. The various steps of glycolysis are depicted in Figure 12.1. In glycolysis, a chain of ten reactions, under the control of different enzymes, takes place to produce pyruvate from glucose. While studying the steps of glycolysis, please note the steps at which utilisation or synthesis of ATP or (in this case) NADH + H^+ take place.

ATP is utilised at two steps: first in the conversion of glucose into glucose 6-phosphate and second in the conversion of fructose 6-phosphate to fructose 1, 6-bisphosphate.

The fructose 1, 6-bisphosphate is split into dihydroxyacetone phosphate and 3-phosphoglyceraldehyde (PGAL). We find that there is one step where NADH + H^+ is formed from NAD^+; this is when 3-phosphoglyceraldehyde (PGAL) is converted to 1, 3-bisphosphoglycerate (BPGA). Two redox-equivalents are removed (in the form of two hydrogen atoms) from PGAL and transferred to a molecule of NAD^+. PGAL is oxidised and with inorganic phosphate to get converted into BPGA. The conversion of BPGA to 3-phosphoglyceric acid (PGA), is also an energy yielding process; this energy is trapped by the formation of ATP. Another ATP is synthesised during the conversion of PEP to pyruvic acid. ***Can you then calculate how many ATP molecules are directly synthesised in this pathway from one glucose molecule?***

Pyruvic acid is then the key product of glycolysis. What is the metabolic fate of pyruvate? This depends on the cellular need.

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There are three major ways in which different cells handle pyruvic acid produced by glycolysis. These are lactic acid fermentation, alcoholic fermentation and aerobic respiration. Fermentation takes place under anaerobic conditions in many prokaryotes and unicellular eukaryotes. For the complete oxidation of glucose to CO_2 and H_2O, however, organisms adopt Krebs' cycle which is also called as aerobic respiration. This requires O_2 supply.

12.3 FERMENTATION

In fermentation, say by yeast, the incomplete oxidation of glucose is achieved under anaerobic conditions by sets of reactions where pyruvic acid is converted to CO_2 and ethanol. The enzymes, pyruvic acid decarboxylase and alcohol dehydrogenase catalyse these reactions. Other organisms like some bacteria produce lactic acid from pyruvic acid. The steps involved are shown in Figure 12.2. In animal cells also, like muscles during exercise, when oxygen is inadequate for cellular respiration pyruvic acid is reduced to lactic acid by lactate dehydrogenase. The reducing agent is $NADH+H^+$ which is reoxidised to NAD^+ in both the processes.

In both lactic acid and alcohol fermentation not much energy is released; less than seven per cent of the energy in glucose is released and not all of it is trapped as high energy bonds of ATP. Also, the processes are hazardous – either acid or alcohol is produced. What is the net ATPs that is synthesised (calculate how many ATP are synthesised and deduct the number of ATP utilised during glycolysis) when one molecule of glucose is fermented to alcohol or lactic acid? Yeasts poison themselves to death when the concentration of alcohol reaches about 13 per cent. ***What then would be the maximum concentration of alcohol in beverages that are naturally fermented?*** How do you think alcoholic beverages of alcohol content greater than this concentration are obtained?

What then is the process by which organisms can carry out complete oxidation of glucose and extract the energy stored to

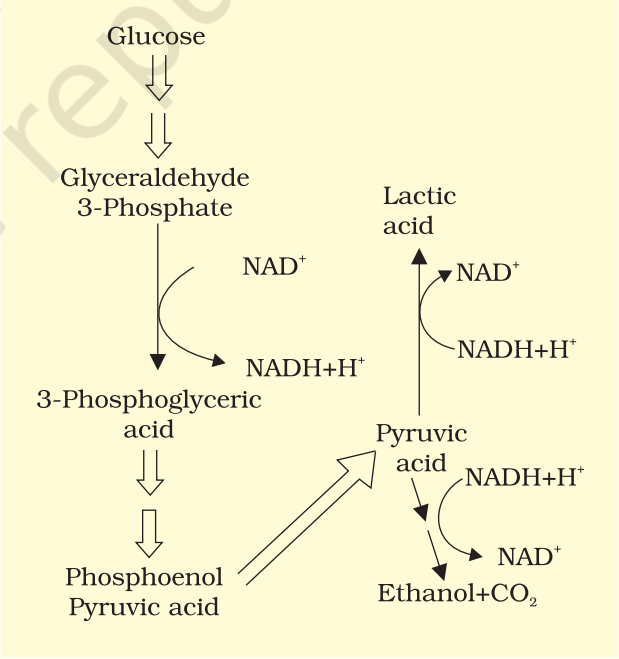

Figure 12.2 Major pathways of anaerobic respiration

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synthesise a larger number of ATP molecules needed for cellular metabolism? In eukaryotes these steps take place within the mitochondria and this requires O_2. **Aerobic respiration** is the process that leads to a complete oxidation of organic substances in the presence of oxygen, and releases CO_2, water and a large amount of energy present in the substrate. This type of respiration is most common in higher organisms. We will look at these processes in the next section.

12.4 AEROBIC RESPIRATION

For aerobic respiration to take place within the mitochondria, the final product of glycolysis, pyruvate is transported from the cytoplasm into the mitochondria. The crucial events in aerobic respiration are:

- The complete oxidation of pyruvate by the stepwise removal of all the hydrogen atoms, leaving three molecules of CO_2.
- The passing on of the electrons removed as part of the hydrogen atoms to molecular O_2 with simultaneous synthesis of ATP.

What is interesting to note is that the first process takes place in the matrix of the mitochondria while the second process is located on the inner membrane of the mitochondria.

Pyruvate, which is formed by the glycolytic catabolism of carbohydrates in the cytosol, after it enters mitochondrial matrix undergoes oxidative decarboxylation by a complex set of reactions catalysed by pyruvic dehydrogenase. The reactions catalysed by pyruvic dehydrogenase require the participation of several coenzymes, including NAD^+ and Coenzyme A.

$$\text{Pyruvic acid} + \text{CoA} + \text{NAD}^+ \xrightarrow[\text{Pyruvate dehydrogenase}]{\text{Mg}^{2+}} \text{Acetyl CoA} + \text{CO}_2 + \text{NADH} + \text{H}^+$$

During this process, two molecules of NADH are produced from the metabolism of two molecules of pyruvic acid (produced from one glucose molecule during glycolysis).

The acetyl CoA then enters a cyclic pathway, tricarboxylic acid cycle, more commonly called as Krebs' cycle after the scientist Hans Krebs who first elucidated it.

12.4.1 Tricarboxylic Acid Cycle

The TCA cycle starts with the condensation of acetyl group with oxaloacetic acid (OAA) and water to yield citric acid (Figure 12.3). The reaction is catalysed by the enzyme citrate synthase and a molecule of CoA is released. Citrate is then isomerised to isocitrate. It is followed by two successive steps of decarboxylation, leading to the formation of α-ketoglutaric acid

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and then succinyl-CoA. In the remaining steps of citric acid cycle, succinyl-CoA is oxidised to OAA allowing the cycle to continue. During the conversion of succinyl-CoA to succinic acid a molecule of GTP is synthesised. This is a substrate level phosphorylation. In a coupled reaction GTP is converted to GDP with the simultaneous synthesis of ATP from ADP. Also there are three points in the cycle where NAD^+ is reduced to NADH + H^+ and one point where FAD^+ is reduced to $FADH_2$. The continued oxidation of acetyl CoA via the TCA cycle requires the continued replenishment of oxaloacetic acid, the first member of the cycle. In addition it also requires regeneration of NAD^+ and FAD^+ from NADH and $FADH_2$ respectively. The summary equation for this phase of respiration may be written as follows:

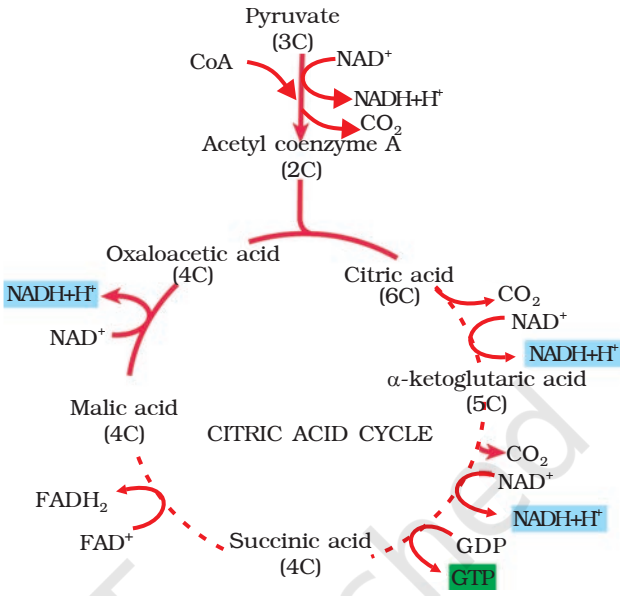

Figure 12.3 The Citric acid cycle

$$\text{Pyruvic acid} + 4NAD^+ + FAD^+ + 2H_2O + ADP + Pi \xrightarrow{\text{Mitochondrial Matrix}} 3CO_2 + 4NADH + 4H^+ + FADH_2 + ATP$$

We have till now seen that glucose has been broken down to release CO_2 and eight molecules of NADH + H^+ and two of $FADH_2$ have been synthesised besides just two molecules of ATP in TCA cycle. You may be wondering why we have been discussing respiration at all – neither O_2 has come into the picture nor the promised large number of ATP has yet been synthesised. Also what is the role of the NADH + H^+ and $FADH_2$ that is synthesised? Let us now understand the role of O_2 in respiration and how ATP is synthesised.

12.4.2 Electron Transport System (ETS) and Oxidative Phosphorylation

The following steps in the respiratory process are to release and utilise the energy stored in NADH+H^+ and $FADH_2$. This is accomplished when they are oxidised through the electron transport system and the electrons are passed on to O_2 resulting in the formation of H_2O. The metabolic pathway through which the electron passes from one carrier to another, is called the ***electron transport system*** (ETS) (Figure 12.4) and it is present in the inner mitochondrial membrane. Electrons from NADH

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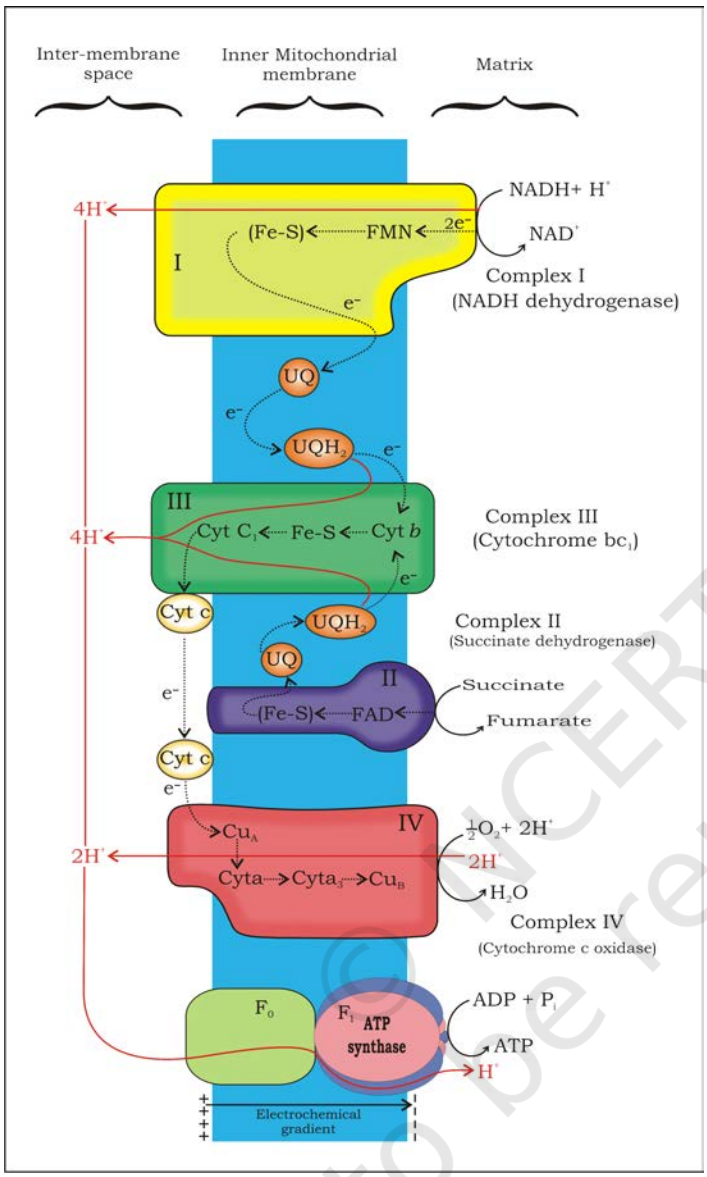

Figure 12.4 Electron Transport System (ETS)

produced in the mitochondrial matrix during citric acid cycle are oxidised by an NADH dehydrogenase (complex I), and electrons are then transferred to ubiquinone located within the inner membrane. Ubiquinone also receives reducing equivalents via $FADH_2$ (complex II) that is generated during oxidation of succinate in the citric acid cycle. The reduced ubiquinone (ubiquinol) is then oxidised with the transfer of electrons to cytochrome *c* via cytochrome bc_1 complex (complex III). Cytochrome *c* is a small protein attached to the outer surface of the inner membrane and acts as a mobile carrier for transfer of electrons between complex III and IV. Complex IV refers to cytochrome *c* oxidase complex containing cytochromes *a* and a_3, and two copper centres.

When the electrons pass from one carrier to another via complex I to IV in the electron transport chain, they are coupled to ATP synthase (complex V) for the production of ATP from ADP and inorganic phosphate. The number of ATP molecules synthesised depends on the nature of the electron donor. Oxidation of one molecule of NADH gives rise to 3 molecules of ATP, while that of one molecule of $FADH_2$ produces 2 molecules of ATP. Although the aerobic process of respiration takes place only in the presence of oxygen, the role of oxygen is limited to the terminal stage of the process. Yet, the presence of oxygen is vital, since it drives the whole process by removing hydrogen from the system. Oxygen acts as the final hydrogen acceptor. Unlike photophosphorylation where it is the light energy that is utilised for the production of proton gradient required for phosphorylation, in respiration it is the energy of oxidation-reduction utilised for the same process. It is for this reason that the process is called oxidative phosphorylation.

You have already studied about the mechanism of membrane-linked ATP synthesis as explained by chemiosmotic hypothesis in the earlier chapter. As mentioned earlier, the energy released during the electron

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transport system is utilised in synthesising ATP with the help of ATP synthase (complex V). This complex consists of two major components, F_1 and F_0 (Figure 12.5). The F_1 headpiece is a peripheral membrane protein complex and contains the site for synthesis of ATP from ADP and inorganic phosphate. F_0 is an integral membrane protein complex that forms the channel through which protons cross the inner membrane. The passage of protons through the channel is coupled to the catalytic site of the F_1 component for the production of ATP. For each ATP produced, $4H^+$ pass through F_0 from the intermembrane space to the matrix down the electrochemical proton gradient.

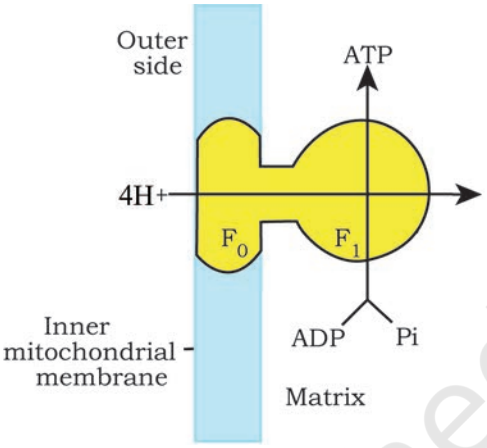

Figure 12.5 Diagramatic presentation of ATP synthesis in mitochondria

12.5 THE RESPIRATORY BALANCE SHEET

It is possible to make calculations of the net gain of ATP for every glucose molecule oxidised; but in reality this can remain only a theoretical exercise. These calculations can be made only on certain assumptions that:

- There is a sequential, orderly pathway functioning, with one substrate forming the next and with glycolysis, TCA cycle and ETS pathway following one after another.
- The NADH synthesised in glycolysis is transferred into the mitochondria and undergoes oxidative phosphorylation.
- None of the intermediates in the pathway are utilised to synthesise any other compound.
- Only glucose is being respired – no other alternative substrates are entering in the pathway at any of the intermediary stages.

But this kind of assumptions are not really valid in a living system; all pathways work simultaneously and do not take place one after another; substrates enter the pathways and are withdrawn from it as and when necessary; ATP is utilised as and when needed; enzymatic rates are controlled by multiple means. Yet, it is useful to do this exercise to appreciate the beauty and efficiency of the living system in extraction and storing energy. Hence, there can be a net gain of 38 ATP molecules during aerobic respiration of one molecule of glucose.

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Now let us compare fermentation and aerobic respiration:

- Fermentation accounts for only a partial breakdown of glucose whereas in aerobic respiration it is completely degraded to CO_2 and H_2O.
- In fermentation there is a net gain of only two molecules of ATP for each molecule of glucose degraded to pyruvic acid whereas many more molecules of ATP are generated under aerobic conditions.
- NADH is oxidised to NAD^+ rather slowly in fermentation, however the reaction is very vigorous in case of aerobic respiration.

12.6 AMPHIBOLIC PATHWAY

Glucose is the favoured substrate for respiration. All carbohydrates are usually first converted into glucose before they are used for respiration. Other substrates can also be respired, as has been mentioned earlier, but then they do not enter the respiratory pathway at the first step. See Figure 12.6 to see the points of entry of different substrates in the respiratory pathway. Fats would need to be broken down into glycerol and fatty acids first. If fatty acids were to be respired they would first be degraded to acetyl CoA and enter the pathway. Glycerol would enter the pathway after being converted to PGAL. The proteins would be degraded by proteases and the individual amino acids (after deamination) depending on their structure would enter the pathway at some stage within the Krebs' cycle or even as pyruvate or acetyl CoA.

Since respiration involves breakdown of substrates, the respiratory process has traditionally been considered a catabolic process and the respiratory pathway as a catabolic pathway. But is this understanding correct? We have discussed above, at which points in the respiratory pathway different substrates would enter if they were to be respired and used to derive energy. What is important to recognise is that it is these very compounds that would be withdrawn from the respiratory pathway for the synthesis of the said substrates. Hence, fatty acids would be broken down to acetyl CoA before entering the respiratory pathway when it is used as a substrate. But when the organism needs to synthesise fatty acids, acetyl CoA would be withdrawn from the respiratory pathway for it. Hence, the respiratory pathway comes into the picture both during breakdown and synthesis of fatty acids. Similarly, during breakdown and synthesis of protein too, respiratory intermediates form the link. Breaking down processes within the living organism is catabolism, and synthesis is anabolism. Because the respiratory pathway is involved in both anabolism and catabolism, it would hence be better to consider the respiratory pathway as an **amphibolic pathway** rather than as a catabolic one.

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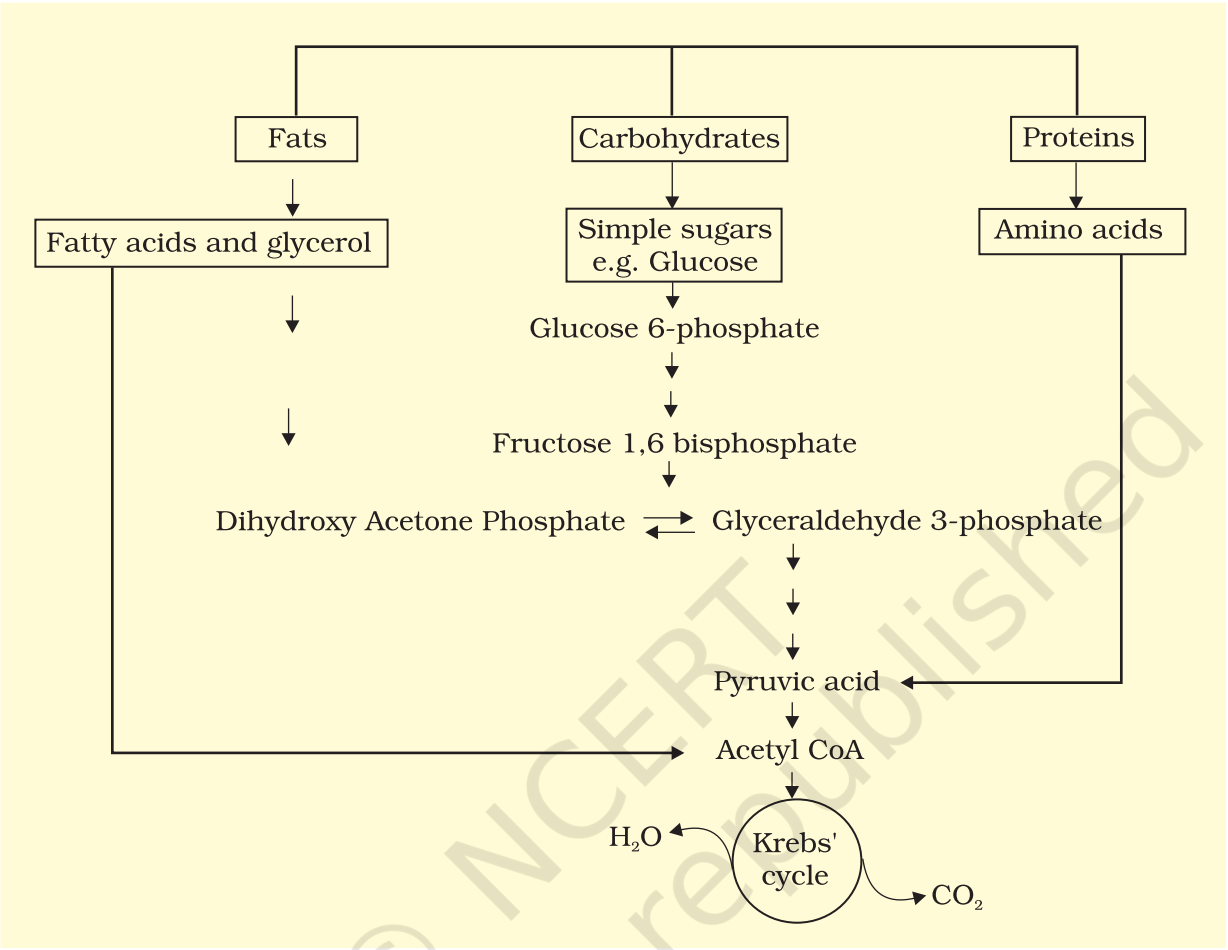

Figure 12.6 Interrelationship among metabolic pathways showing respiration mediated breakdown of different organic molecules to CO_2 and H_20

12.7 RESPIRATORY QUOTIENT

Let us now look at another aspect of respiration. As you know, during aerobic respiration, O_2 is consumed and CO_2 is released. The ratio of the volume of CO_2 evolved to the volume of O_2 consumed in respiration is called the **respiratory quotient** (RQ) or respiratory ratio.

$$RQ = \frac{\text{volume of } CO_2 \text{ evolved}}{\text{volume of } O_2 \text{ consumed}}$$

The respiratory quotient depends upon the type of respiratory substrate used during respiration.

When carbohydrates are used as substrate and are completely oxidised, the RQ will be 1, because equal amounts of CO_2 and O_2 are evolved and consumed, respectively, as shown in the equation below :

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$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

$$RQ = \frac{6CO_2}{6O_2} = 1.0$$

When fats are used in respiration, the RQ is less than 1. Calculations for a fatty acid, tripalmitin, if used as a substrate is shown:

$$2(C_{51}H_{98}O_6) + 145O_2 \longrightarrow 102CO_2 + 98H_2O + \text{energy}$$

Tripalmitin

$$RQ = \frac{102CO_2}{145O_2} = 0.7$$

When proteins are respiratory substrates the ratio would be about 0.9.

What is important to recognise is that in living organisms, respiratory substrates are often more than one; pure proteins or fats are never used as respiratory substrates.

SUMMARY

Plants unlike animals have no special systems for breathing or gaseous exchange. Stomata and lenticels allow gaseous exchange by diffusion. Almost all living cells in a plant have their surfaces exposed to air.

The breaking of CC bonds of complex organic molecules by oxidation leading to the release of a lot of energy is called cellular respiration. Glucose is the favoured substrate for respiration. Fats and proteins can also be broken down to yield energy. The initial stage of cellular respiration takes place in the cytoplasm. Each glucose molecule is broken through a series of enzyme catalysed reactions into two molecules of pyruvic acid. This process is called glycolysis. The fate of the pyruvate depends on the availability of oxygen and the organism. Under anaerobic conditions either lactic acid fermentation or alcohol fermentation occurs. Fermentation takes place under anaerobic conditions in many prokaryotes, unicellular eukaryotes and in germinating seeds. In eukaryotic organisms aerobic respiration occurs in the presence of oxygen. Pyruvic acid is transported into the mitochondria where it is converted into acetyl CoA with the release of CO_2. Acetyl CoA then enters the tricarboxylic acid pathway or Krebs' cycle operating in the matrix of the mitochondria. NADH + H^+ and $FADH_2$ are generated in the Krebs' cycle. The energy in these molecules as well as that in the NADH + H^+ synthesised during glycolysis are used to synthesise ATP. This is accomplished through a

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system of electron carriers called electron transport system (ETS) located on the inner membrane of the mitochondria. The electrons, as they move through the system, release enough energy that are trapped to synthesise ATP. This is called oxidative phosphorylation. In this process O_2 is the ultimate acceptor of electrons and it gets reduced to water.

The respiratory pathway is an amphibolic pathway as it involves both anabolism and catabolism. The respiratory quotient depends upon the type of respiratory substance used during respiration.

EXERCISES

1. Differentiate between
   (a) Respiration and Combustion
   (b) Glycolysis and Krebs' cycle
   (c) Aerobic respiration and Fermentation
2. What are respiratory substrates? Name the most common respiratory substrate.
3. Give the schematic representation of glycolysis?
4. What are the main steps in aerobic respiration? Where does it take place?
5. Give the schematic representation of an overall view of Krebs' cycle.
6. Explain ETS.
7. Distinguish between the following:
   (a) Aerobic respiration and Anaerobic respiration
   (b) Glycolysis and Fermentation
   (c) Glycolysis and Citric acid Cycle
8. What are the assumptions made during the calculation of net gain of ATP?
9. Discuss "The respiratory pathway is an amphibolic pathway."
10. Define RQ. What is its value for fats?
11. What is oxidative phosphorylation?
12. What is the significance of step-wise release of energy in respiration?

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Chapter 13
Plant Growth and Development

13.1 *Growth*

13.2 *Differentiation, Dedifferentiation and Redifferentiation*

13.3 *Development*

13.4 *Plant Growth Regulators*

You have already studied the organisation of a flowering plant in Chapter 5. Have you ever thought about where and how the structures like roots, stems, leaves, flowers, fruits and seeds arise and that too in an orderly sequence? You are, by now, aware of the terms seed, seedling, plantlet, mature plant. You have also seen that trees continue to increase in height or girth over a period of time. However, the leaves, flowers and fruits of the same tree not only have limited dimensions but also appear and fall periodically and some time repeatedly. Why does vegetative phase precede flowering in a plant? All plant organs are made up of a variety of tissues; is there any relationship between the structure of a cell, a tissue, an organ and the function they perform? Can the structure and the function of these be altered? All cells of a plant are descendents of the zygote. The question is, then, why and how do they have different structural and functional attributes? Development is the sum of two processes: growth and differentiation. To begin with, it is essential and sufficient to know that the development of a mature plant from a zygote (fertilised egg) follow a precise and highly ordered succession of events. During this process a complex body organisation is formed that produces roots, leaves, branches, flowers, fruits, and seeds, and eventually they die (Figure 13.1). The first step in the process of plant growth is seed germination. The seed germinates when favourable conditions for growth exist in the environment. In absence of such favourable conditions the seeds do not germinate and goes into a period of suspended growth or rest. Once favourable conditions return, the seeds resume metabolic activities and growth takes place.

In this chapter, you shall also study some of the factors which govern and control these developmental processes. These factors are both intrinsic (internal) and extrinsic (external) to the plant.

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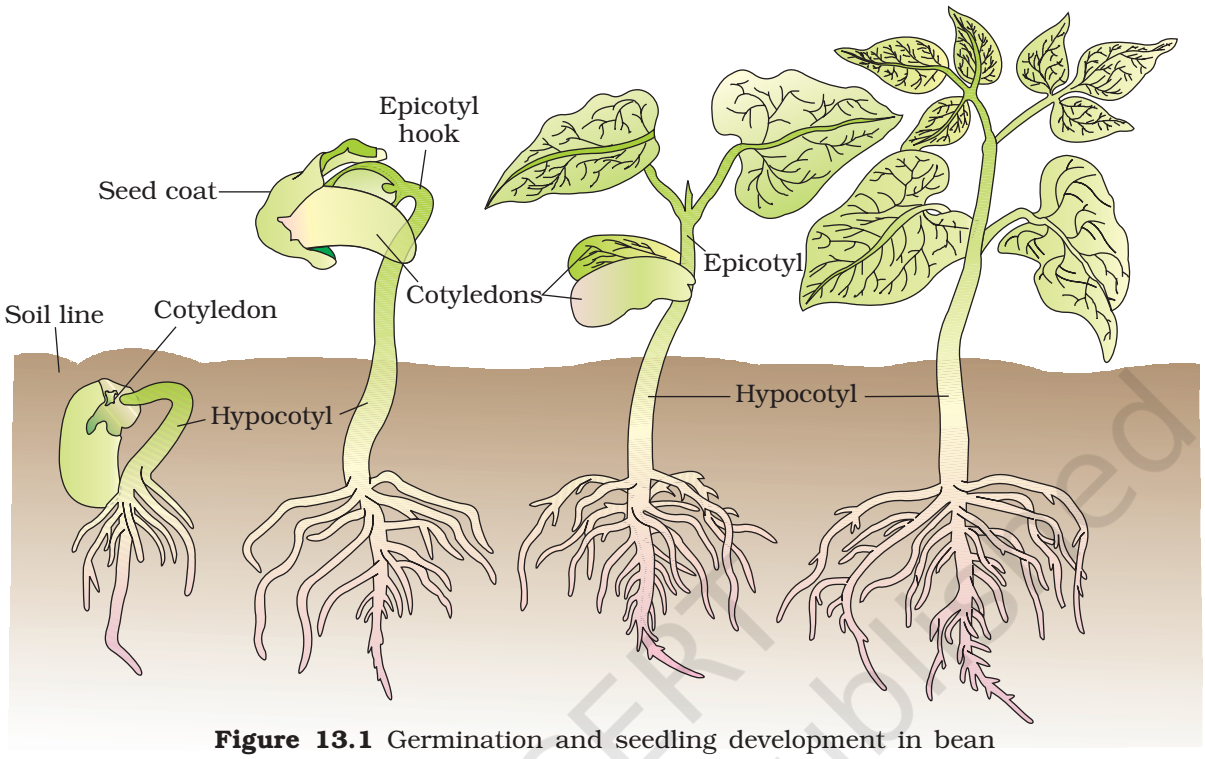

Figure 13.1 Germination and seedling development in bean

13.1 GROWTH

Growth is regarded as one of the most fundamental and conspicuous characteristics of a living being. What is growth? Growth can be defined as an irreversible permanent increase in size of an organ or its parts or even of an individual cell. Generally, growth is accompanied by metabolic processes (both anabolic and catabolic), that occur at the expense of energy. Therefore, for example, expansion of a leaf is growth. How would you describe the swelling of piece of wood when placed in water?

13.1.1 Plant Growth Generally is Indeterminate

Plant growth is unique because plants retain the capacity for unlimited growth throughout their life. This ability of the plants is due to the presence of meristems at certain locations in their body. The cells of such meristems have the capacity to divide and self-perpetuate. The product, however, soon loses the capacity to divide and such cells make up the plant body. This form of growth wherein new cells are always being added to the plant body by the activity of the meristem is called the open form of growth. What would happen if the meristem ceases to divide? Does this ever happen?

In earlier classes, you have studied about the root apical meristem and the shoot apical meristem. You know that they are responsible for

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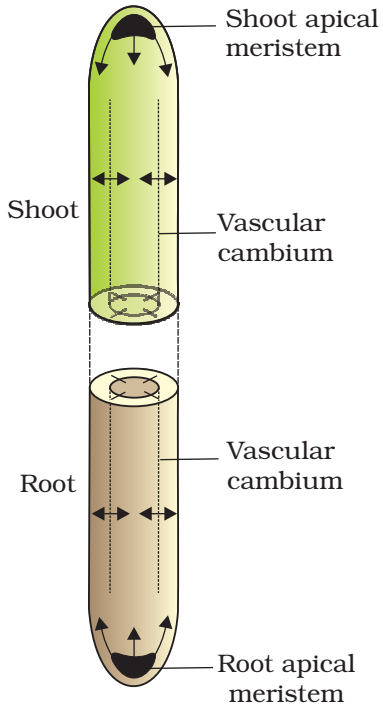

Figure 13.2 Diagrammatic representation of locations of root apical meristem, shoot aplical meristem and vascular cambium. Arrows exhibit the direction of growth of cells and organ

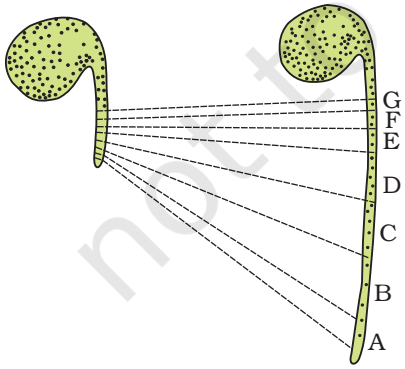

Figure 13.3 Detection of zones of elongation by the parallel line technique. Zones A, B, C, D immediately behind the apex have elongated most.

the primary growth of the plants and principally contribute to the elongation of the plants along their axis. You also know that in dicotyledonous plants and gymnosperms, the lateral meristems, vascular cambium and cork-cambium appear later in life. These are the meristems that cause the increase in the girth of the organs in which they are active. This is known as secondary growth of the plant (see Figure 13.2).

13.1.2 Growth is Measurable

Growth, at a cellular level, is principally a consequence of increase in the amount of protoplasm. Since increase in protoplasm is difficult to measure directly, one generally measures some quantity which is more or less proportional to it. Growth is, therefore, measured by a variety of parameters some of which are: increase in fresh weight, dry weight, length, area, volume and cell number. You may find it amazing to know that one single maize root apical mersitem can give rise to more than 17,500 new cells per hour, whereas cells in a watermelon may increase in size by upto 3,50,000 times. In the former, growth is expressed as increase in cell number; the latter expresses growth as increase in size of the cell. While the growth of a pollen tube is measured in terms of its length, an increase in surface area denotes the growth in a dorsiventral leaf.

13.1.3 Phases of Growth

The period of growth is generally divided into three phases, namely, meristematic, elongation and maturation (Figure 13.3). Let us understand this by looking at the root tips. The constantly dividing cells, both at the root apex and the shoot apex, represent the meristematic phase of growth. The cells in this region are rich in protoplasm, possess large conspicuous nuclei. Their cell walls are primary in nature, thin and cellulosic with abundant plasmodesmatal connections. The cells proximal (just next, away from the tip) to the

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meristematic zone represent the phase of elongation. Increased vacuolation, cell enlargement and new cell wall deposition are the characteristics of the cells in this phase. Further away from the apex, i.e., more proximal to the phase of elongation, lies the portion of axis which is undergoing the phase of maturation. The cells of this zone, attain their maximal size in terms of wall thickening and protoplasmic modifications. Most of the tissues and cell types you have studied in earlier classes represent this phase.

13.1.4 Growth Rates

The increased growth per unit time is termed as growth rate. Thus, rate of growth can be expressed mathematically. An organism, or a part of the organism can produce more cells in a variety of ways.

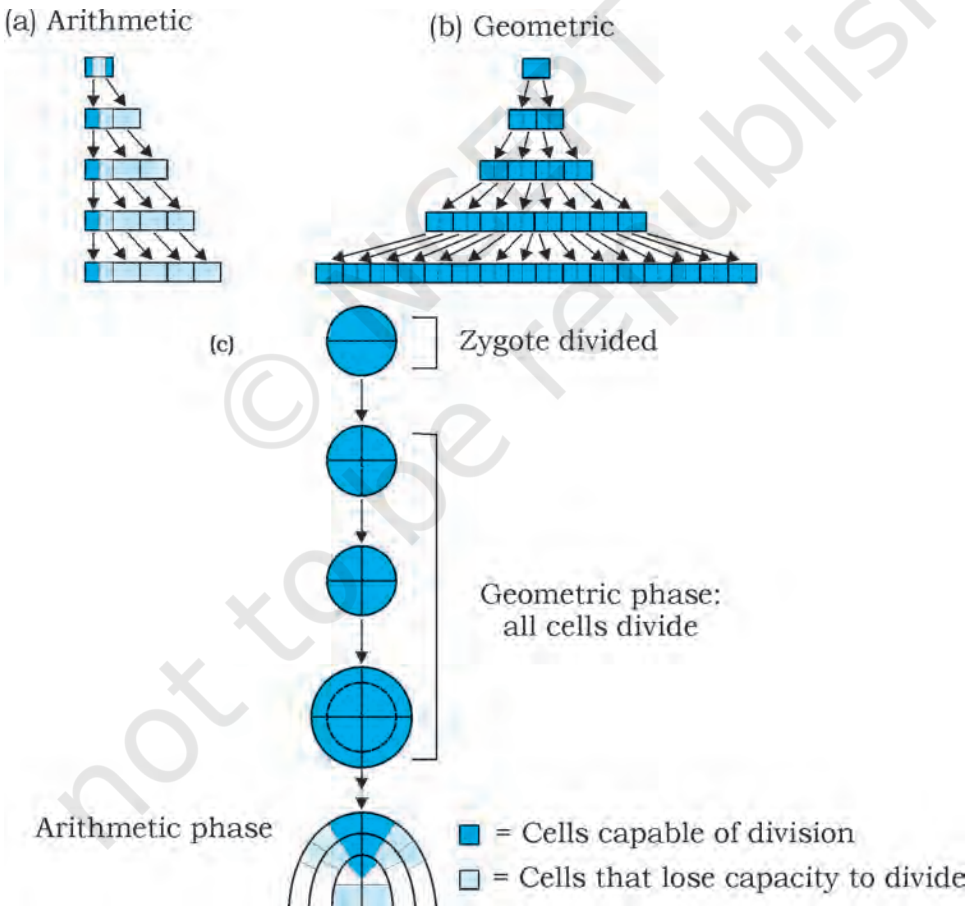

Figure 13.4 Diagrammatic representation of : (a) Arithmetic (b) Geometric growth and (c) Stages during embryo development showing geometric and arithematic phases

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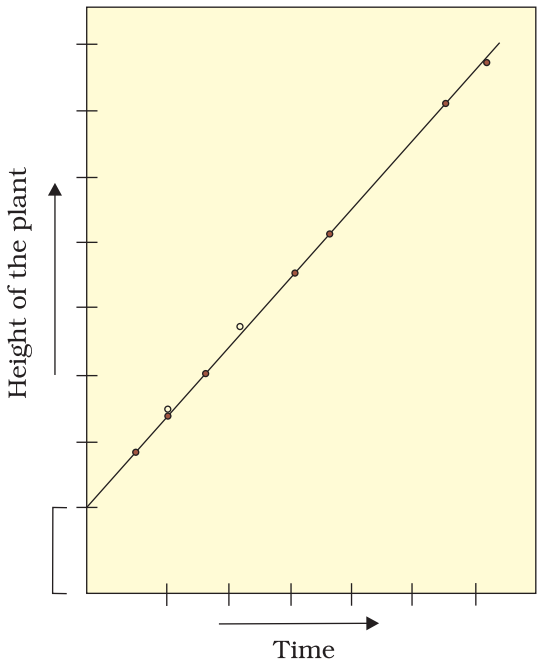

Figure 13.5 Constant linear growth, a plot of length L against time t

The growth rate shows an increase that may be arithmetic or geometrical (Figure 13.4).

In arithmetic growth, following mitotic cell division, only one daughter cell continues to divide while the other differentiates and matures. The simplest expression of arithmetic growth is exemplified by a root elongating at a constant rate. Look at Figure 13.5. On plotting the length of the organ against time, a linear curve is obtained. Mathematically, it is expressed as

$L_t = L_0 + rt$

L_t = length at time 't'

L_0 = length at time 'zero'

r = growth rate / elongation per unit time.

Let us now see what happens in geometrical growth. In most systems, the initial growth is slow (lag phase), and it increases rapidly thereafter – at an exponential rate (log or exponential phase). Here, both the progeny cells following mitotic cell division retain the ability to divide and continue to do so. However, with limited nutrient supply, the growth slows down leading to a stationary phase. If we plot the parameter of growth against time, we get a typical sigmoid or S-curve (Figure 13.6). A sigmoid curve is a characteristic of living organism growing in a natural environment. It is typical for all cells, tissues and organs of a plant. *Can you think of more similar examples? What kind of a curve can you expect in a tree showing seasonal activities?*

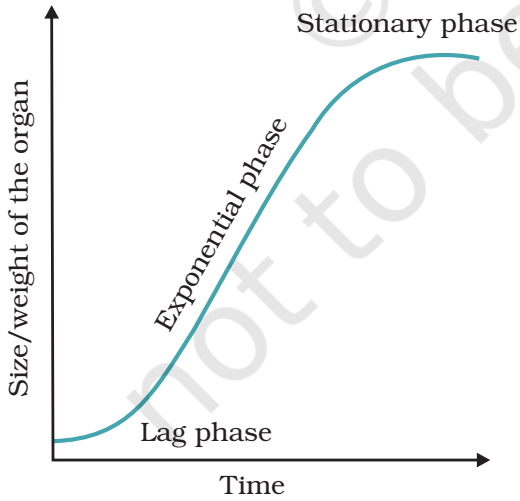

Figure 13.6 An idealised sigmoid growth curve typical of cells in culture, and many higher plants and plant organs

The exponential growth can be expressed as

$W_1 = W_0 e^{rt}$

W_1 = final size (weight, height, number etc.)

W_0 = initial size at the beginning of the period

r = growth rate

t = time of growth

e = base of natural logarithms

Here, r is the relative growth rate and is also the measure of the ability of the plant to produce new plant material, referred to as efficiency index. Hence, the final size of W_1 depends on the initial size, W_0.

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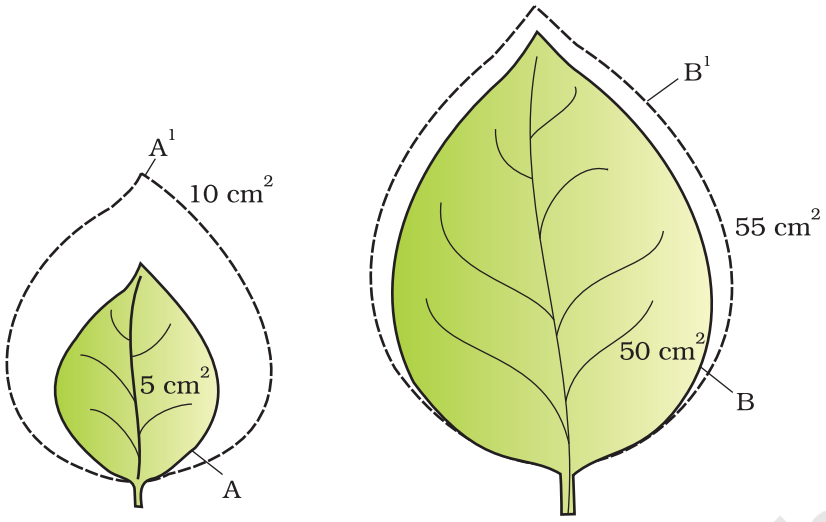

Figure 13.7 Diagrammatic comparison of absolute and relative growth rates. Both leaves A and B have increased their area by 5 cm^2 in a given time to produce A^1, B^1 leaves.

Quantitative comparisons between the growth of living system can also be made in two ways : (i) measurement and the comparison of total growth per unit time is called the absolute growth rate. (ii) The growth of the given system per unit time expressed on a common basis, e.g., per unit initial parameter is called the relative growth rate. In Figure 13.7 two leaves, A and B, are drawn that are of different sizes but shows absolute increase in area in the given time to give leaves, A^1 and B^1. However, one of them shows much higher relative growth rate. Which one and why?

13.1.5 Conditions for Growth

Why do you not try to write down what you think are necessary conditions for growth? This list may have water, oxygen and nutrients as very essential elements for growth. The plant cells grow in size by cell enlargement which in turn requires water. Turgidity of cells helps in extension growth. Thus, plant growth and further development is intimately linked to the water status of the plant. Water also provides the medium for enzymatic activities needed for growth. Oxygen helps in releasing metabolic energy essential for growth activities. Nutrients (macro and micro essential elements) are required by plants for the synthesis of protoplasm and act as source of energy.

In addition, every plant organism has an optimum temperature range best suited for its growth. Any deviation from this range could be detrimental to its survival. Environmental signals such as light and gravity also affect certain phases/stages of growth.

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13.2 DIFFERENTIATION, DEDIFFERENTIATION AND REDIFFERENTIATION

The cells derived from root apical and shoot-apical meristems and cambium differentiate and mature to perform specific functions. This act leading to maturation is termed as **differentiation**. During differentiation, cells undergo few to major structural changes both in their cell walls and protoplasm. For example, to form a tracheary element, the cells would lose their protoplasm. They also develop a very strong, elastic, lignocellulosic secondary cell walls, to carry water to long distances even under extreme tension. Try to correlate the various anatomical features you encounter in plants to the functions they perform.

Plants show another interesting phenomenon. The living differentiated cells, that by now have lost the capacity to divide can regain the capacity of division under certain conditions. This phenomenon is termed as **dedifferentiation**. For example, formation of meristems – interfascicular cambium and cork cambium from fully differentiated parenchyma cells. While doing so, such meristems/tissues are able to divide and produce cells that once again lose the capacity to divide but mature to perform specific functions, i.e., get **redifferentiated**. List some of the tissues in a woody dicotyledenous plant that are the products of redifferentiation. How would you describe a tumour? What would you call the parenchyma cells that are made to divide under controlled laboratory conditions during plant tissue culture?

Recall, in Section 13.1.1, we have mentioned that the growth in plants is open, i.e., it can be indeterminate or determinate. Now, we may say that even differentiation in plants is open, because cells/tissues arising out of the same meristem have different structures at maturity. The final structure at maturity of a cell/tissue is also determined by the location of the cell within. For example, cells positioned away from root apical meristems differentiate as root-cap cells, while those pushed to the periphery mature as epidermis. Can you add a few more examples of open differentiation correlating the position of a cell to its position in an organ?

13.3 DEVELOPMENT

Development is a term that includes all changes that an organism goes through during its life cycle from germination of the seed to senescence. Diagrammatic representation of the sequence of processes which constitute the development of a cell of a higher plant is given in Figure 13.8. It is also applicable to tissues/organs.

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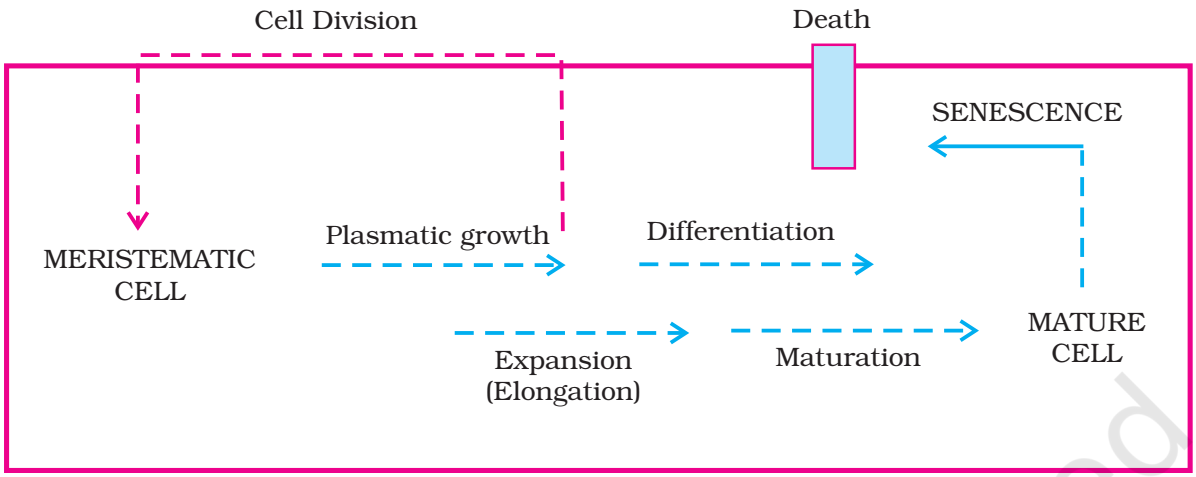

Figure 13.8 Sequence of the developmental process in a plant cell

Plants follow different pathways in response to environment or phases of life to form different kinds of structures. This ability is called **plasticity,** e.g., heterophylly in cotton, coriander and larkspur. In such plants, the leaves of the juvenile plant are different in shape from those in mature plants. On the other hand, difference in shapes of leaves produced in air and those produced in water in buttercup also represent the heterophyllous development due to environment (Figure 13.9). This phenomenon of heterophylly is an example of plasticity.

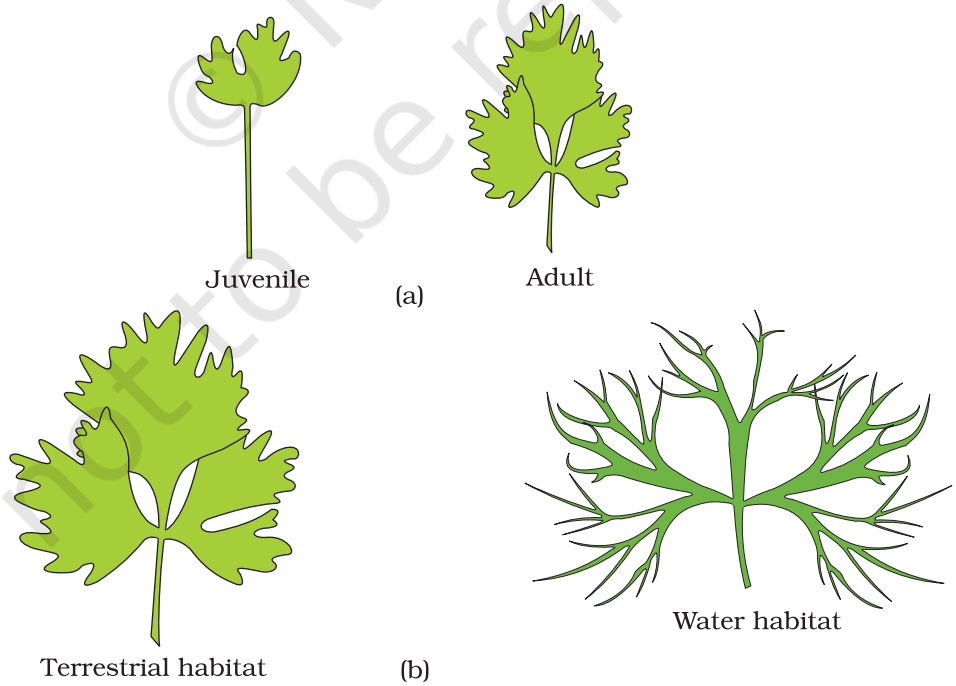

Figure 13.9 Heterophylly in (a) larkspur and (b) buttercup

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Thus, growth, differentiation and development are very closely related events in the life of a plant. Broadly, development is considered as the sum of growth and differentiation. Development in plants (i.e., both growth and differentiation) is under the control of intrinsic and extrinsic factors. The former includes both intracellular (genetic) or intercellular factors (chemicals such as plant growth regulators) while the latter includes light, temperature, water, oxygen, nutrition, etc.

13.4 PLANT GROWTH REGULATORS

13.4.1 Characteristics

The plant growth regulators (PGRs) are small, simple molecules of diverse chemical composition. They could be indole compounds (indole-3-acetic acid, IAA); adenine derivatives (N^6-furfurylamino purine, kinetin), derivatives of carotenoids (abscisic acid, ABA); terpenes (gibberellic acid, GA_3) or gases (ethylene, C_2H_4). Plant growth regulators are variously described as plant growth substances, plant hormones or phytohormones in literature.

The PGRs can be broadly divided into two groups based on their functions in a living plant body. One group of PGRs are involved in growth promoting activities, such as cell division, cell enlargement, pattern formation, tropic growth, flowering, fruiting and seed formation. These are also called plant growth promoters, e.g., auxins, gibberellins and cytokinins. The PGRs of the other group play an important role in plant responses to wounds and stresses of biotic and abiotic origin. They are also involved in various growth inhibiting activities such as dormancy and abscission. The PGR abscisic acid belongs to this group. The gaseous PGR, ethylene, could fit either of the groups, but it is largely an inhibitor of growth activities.

13.4.2 The Discovery of Plant Growth Regulators

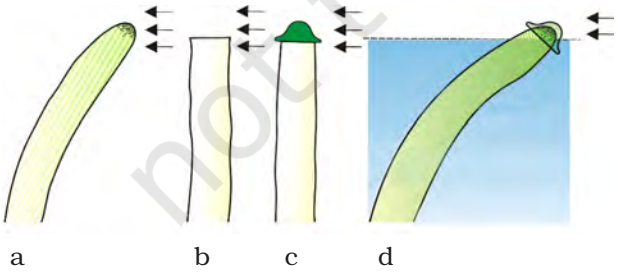

Figure 13.10 Experiment used to demonstrate that tip of the coleoptile is the source of auxin. Arrows indicate direction of light

Interestingly, the discovery of each of the five major groups of PGRs have been accidental. All this started with the observation of Charles Darwin and his son Francis Darwin when they observed that the coleoptiles of canary grass responded to unilateral illumination by growing towards the light source (phototropism). After a series of experiments, it was concluded that the tip of coleoptile was the site of transmittable influence that caused the bending of the entire coleoptile (Figure 13.10). Auxin was isolated by F.W. Went from tips of coleoptiles of oat seedlings.

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The 'bakanae' (foolish seedling) disease of rice seedlings, was caused by a fungal pathogen *Gibberella fujikuroi*. E. Kurosawa (1926) reported the appearance of symptoms of the disease in rice seedlings when they were treated with sterile filtrates of the fungus. The active substances were later identified as gibberellic acid.

F. Skoog and his co-workers observed that from the internodal segments of tobacco stems, the callus (a mass of undifferentiated cells) proliferated only if, in addition to auxins the nutrients medium was supplemented with one of the following: extracts of vascular tissues, yeast extract, coconut milk or DNA. Miller et al. (1955), later identified and crystallised the cytokinesis promoting active substance that they termed kinetin.

During mid-1960s, three independent researches reported the purification and chemical characterisation of three different kinds of inhibitors: inhibitor-B, abscission II and dormin. Later all the three were proved to be chemically identical. It was named abscisic acid (ABA).

H.H. Cousins (1910) confirmed the release of a volatile substance from ripened oranges that hastened the ripening of stored unripened bananas. Later this volatile substance was identified as ethylene, a gaseous PGR.

Let us study some of the physiological effects of these five categories of PGRs in the next section.

13.4.3 Physiological Effects of Plant Growth Regulators

13.4.3.1 Auxins

Auxins (from Greek 'auxein' : to grow) was first isolated from human urine. The term 'auxin' is applied to the indole-3-acetic acid (IAA), and to other natural and synthetic compounds having certain growth regulating properties. They are generally produced by the growing apices of the stems and roots, from where they migrate to the regions of their action. Auxins like IAA and indole butyric acid (IBA) have been isolated from plants. NAA (naphthalene acetic acid) and 2, 4-D (2, 4-dichlorophenoxyacetic) are synthetic auxins. All these auxins have been used extensively in agricultural and horticultural practices.

They help to initiate rooting in stem cuttings, an application widely used for plant propagation. Auxins promote flowering e.g. in pineapples. They help to prevent fruit and leaf drop at early stages but promote the abscission of older mature leaves and fruits.

In most higher plants, the growing apical bud inhibits the growth of the lateral (axillary) buds, a phenomenon called **apical dominance**. Removal of shoot tips (decapitation) usually results in the growth of lateral buds (Figure 13.11). It is widely applied in tea plantations and hedge-making. Can you explain why?

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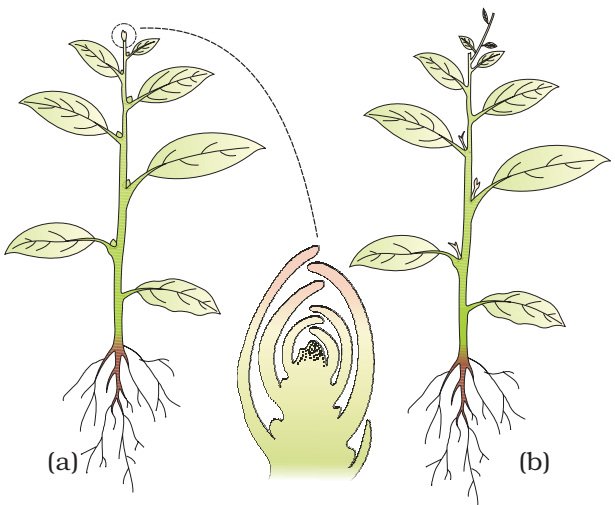

Figure 13.11 Apical dominance in plants : (a) A plant with apical bud intact (b) A plant with apical bud removed Note the growth of lateral buds into branches after decapitation.

Auxins also induce parthenocarpy, e.g., in tomatoes. They are widely used as herbicides. 2, 4-D, widely used to kill dicotyledonous weeds, does not affect mature monocotyledonous plants. It is used to prepare weed-free lawns by gardeners. Auxin also controls xylem differentiation and helps in cell division.

13.4.3.2 Gibberellins

Gibberellins are another kind of promotory PGR. There are more than 100 gibberellins reported from widely different organisms such as fungi and higher plants. They are denoted as GA_1, GA_2, GA_3 and so on. However, Gibberellic acid (GA_3) was one of the first gibberellins to be discovered and remains the most intensively studied form. All GAs are acidic. They produce a wide range of physiological responses in the plants. Their ability to cause an increase in length of axis is used to increase the length of grapes stalks. Gibberellins, cause fruits like apple to elongate and improve its shape. They also delay senescence. Thus, the fruits can be left on the tree longer so as to extend the market period. GA_3 is used to speed up the malting process in brewing industry.

Sugarcane stores carbohydrate as sugar in their stems. Spraying sugarcane crop with gibberellins increases the length of the stem, thus increasing the yield by as much as 20 tonnes per acre.

Spraying juvenile conifers with GAs hastens the maturity period, thus leading to early seed production. Gibberellins also promotes bolting (internode elongation just prior to flowering) in beet, cabbages and many plants with rosette habit.

13.4.3.3 Cytokinins

Cytokinins have specific effects on cytokinesis, and were discovered as kinetin (a modified form of adenine, a purine) from the autoclaved herring sperm DNA. Kinetin does not occur naturally in plants. Search for natural substances with cytokinin-like activities led to the isolation of zeatin from corn-kernels and coconut milk. Since the discovery of zeatin, several naturally occurring cytokinins, and some synthetic compounds with cell division promoting activity, have been identified. Natural cytokinins are

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synthesised in regions where rapid cell division occurs, for example, root apices, developing shoot buds, young fruits etc. It helps to produce new leaves, chloroplasts in leaves, lateral shoot growth and adventitious shoot formation. Cytokinins help overcome the apical dominance. They promote nutrient mobilisation which helps in the delay of leaf senescence.

13.4.3.4 Ethylene

Ethylene is a simple gaseous PGR. It is synthesised in large amounts by tissues undergoing senescence and ripening fruits. Influences of ethylene on plants include horizontal growth of seedlings, swelling of the axis and apical hook formation in dicot seedlings. Ethylene promotes senescence and abscission of plant organs especially of leaves and flowers. Ethylene is highly effective in fruit ripening. It enhances the respiration rate during ripening of the fruits. This rise in rate of respiration is called respiratory climactic.

Ethylene breaks seed and bud dormancy, initiates germination in peanut seeds, sprouting of potato tubers. Ethylene promotes rapid internode/petiole elongation in deep water rice plants. It helps leaves/ upper parts of the shoot to remain above water. Ethylene also promotes root growth and root hair formation, thus helping the plants to increase their absorption surface.

Ethylene is used to initiate flowering and for synchronising fruit-set in pineapples. It also induces flowering in mango. Since ethylene regulates so many physiological processes, it is one of the most widely used PGR in agriculture. The most widely used compound as source of ethylene is ethephon. Ethephon in an aqueous solution is readily absorbed and transported within the plant and releases ethylene slowly. Ethephon hastens fruit ripening in tomatoes and apples and accelerates abscission in flowers and fruits (thinning of cotton, cherry, walnut). It promotes female flowers in cucumbers thereby increasing the yield.

13.4.3.5 Abscisic acid

As mentioned earlier, abscisic acid **(ABA)** was discovered for its role in regulating abscission and dormancy. But like other PGRs, it also has other wide ranging effects on plant growth and development. It acts as a general plant growth inhibitor and an inhibitor of plant metabolism. ABA inhibits seed germination. ABA stimulates the closure of stomata and increases the tolerance of plants to various kinds of stresses. Therefore, it is also called the stress hormone. ABA plays an important

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role in seed development, maturation and dormancy. By inducing dormancy, ABA helps seeds to withstand desiccation and other factors unfavourable for growth. In most situations, ABA acts as an antagonist to GAs.

We may summarise that for any and every phase of growth, differentiation and development of plants, one or the other PGR has some role to play. Such roles could be complimentary or antagonistic. These could be individualistic or synergistic.

Similarly, there are a number of events in the life of a plant where more than one PGR interact to affect that event, e.g., dormancy in seeds/ buds, abscission, senescence, apical dominance, etc.

Remember, the role of PGR is of only one kind of intrinsic control. Along with genomic control and extrinsic factors, they play an important role in plant growth and development. Many of the extrinsic factors such as temperature and light, control plant growth and development via PGR. Some of such events could be: vernalisation, flowering, dormancy, seed germination, plant movements, etc.

We shall discuss briefly the role of light and temperature (both of them, the extrinsic factors) on initiation of flowering.

SUMMARY

Growth is one of the most conspicuous events in any living organism. It is an irreversible increase expressed in parameters such as size, area, length, height, volume, cell number etc. It conspicuously involves increased protoplasmic material. In plants, meristems are the sites of growth. Root and shoot apical meristems sometimes alongwith intercalary meristem, contribute to the elongation growth of plant axes. Growth is indeterminate in higher plants. Following cell division in root and shoot apical meristem cells, the growth could be arithmetic or geometrical. Growth may not be and generally is not sustained at a high rate throughout the life of cell/ tissue/organ/organism. One can define three principle phases of growth – the lag, the log and the senescent phase. When a cell loses the capacity to divide, it leads to differentiation. Differentiation results in development of structures that is commensurate with the function the cells finally has to perform. General principles for differentiation for cell, tissues and organs are similar. A differentiated cell may dedifferentiate and then redifferentiate. Since differentiation in plants is open, the development could also be flexible, i.e., the development is the sum of growth and differentiation. Plant exhibit plasticity in development.

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Plant growth and development are under the control of both intrinsic and extrinsic factors. Intercellular intrinsic factors are the chemical substances, called plant growth regulators (PGR). There are diverse groups of PGRs in plants, principally belonging to five groups: auxins, gibberellins, cytokinins, abscisic acid and ethylene. These PGRs are synthesised in various parts of the plant; they control different differentiation and developmental events. Any PGR has diverse physiological effects on plants. Diverse PGRs also manifest similar effects. PGRs may act synergistically or antagonistically. Plant growth and development is also affected by light, temperature, nutrition, oxygen status, gravity and such external factors.

EXERCISES

1. Define growth, differentiation, development, dedifferentiation, redifferentiation, determinate growth, meristem and growth rate.
2. Why is not any one parameter good enough to demonstrate growth throughout the life of a flowering plant?
3. Describe briefly:
   (a) Arithmetic growth
   (b) Geometric growth
   (c) Sigmoid growth curve
   (d) Absolute and relative growth rates
4. List five main groups of natural plant growth regulators. Write a note on discovery, physiological functions and agricultural/horticultural applications of any one of them.
5. Why is abscisic acid also known as stress hormone?
6. 'Both growth and differentiation in higher plants are *open*'. Comment.
7. 'Both a short day plant and a long day plant can produce can flower simultaneously in a given place'. Explain.
8. Which one of the plant growth regulators would you use if you are asked to:
   (a) induce rooting in a twig
   (b) quickly ripen a fruit
   (c) delay leaf senescence
   (d) induce growth in axillary buds
   (e) 'bolt' a rosette plant
   (f) induce immediate stomatal closure in leaves.
9. Would a defoliated plant respond to photoperiodic cycle? Why?

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10. What would be expected to happen if:
    (a) GA_3 is applied to rice seedlings
    (b) dividing cells stop differentiating
    (c) a rotten fruit gets mixed with unripe fruits
    (d) you forget to add cytokinin to the culture medium.

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UNIT 5

HUMAN PHYSIOLOGY

Chapter 14
Breathing and Exchange of Gases

Chapter 15
Body Fluids and Circulation

Chapter 16
Excretory Products and their Elimination

Chapter 17
Locomotion and Movement

Chapter 18
Neural Control and Coordination

Chapter 19
Chemical Coordination and Integration

The reductionist approach to study of life forms resulted in increasing use of physico-chemical concepts and techniques. Majority of these studies employed either surviving tissue model or straightaway cell-free systems. An explosion of knowledge resulted in molecular biology. Molecular physiology became almost synonymous with biochemistry and biophysics. However, it is now being increasingly realised that neither a purely organismic approach nor a purely reductionistic molecular approach would reveal the truth about biological processes or living phenomena. Systems biology makes us believe that all living phenomena are emergent properties due to interaction among components of the system under study. Regulatory network of molecules, supra molecular assemblies, cells, tissues, organisms and indeed, populations and communities, each create emergent properties. In the chapters under this unit, major human physiological processes like, exchange of gases, blood circulation, locomotion and movement are described in cellular and molecular terms. The last two chapters point to the coordination and regulation of body events at the organismic level.

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Alfonso Corti
(1822 – 1888)

Alfonso Corti, Italian anatomist, was born in 1822. Corti began his scientific career studying the cardiovascular systems of reptiles. Later, he turned his attention to the mammalian auditory system. In 1851, he published a paper describing a structure located on the basilar membrane of the cochlea containing hair cells that convert sound vibrations into nerve impulses, the organ of Corti. He died in the year 1888.

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Chapter 14
Breathing and Exchange of Gases

14.1 *Respiratory Organs*

14.2 *Mechanism of Breathing*

14.3 *Exchange of Gases*

14.4 *Transport of Gases*

14.5 *Regulation of Respiration*

14.6 *Disorders of Respiratory System*

As you have read earlier, oxygen (O_2) is utilised by the organisms to indirectly break down simple molecules like glucose, amino acids, fatty acids, etc., to derive energy to perform various activities. Carbon dioxide (CO_2) which is harmful is also released during the above catabolic reactions. It is, therefore, evident that O_2 has to be continuously provided to the cells and CO_2 produced by the cells have to be released out. This process of exchange of O_2 from the atmosphere with CO_2 produced by the cells is called **breathing,** commonly known as **respiration**. Place your hands on your chest; you can feel the chest moving up and down. You know that it is due to breathing. How do we breathe? The respiratory organs and the mechanism of breathing are described in the following sections of this chapter.

14.1 Respiratory Organs

Mechanisms of breathing vary among different groups of animals depending mainly on their habitats and levels of organisation. Lower invertebrates like sponges, coelenterates, flatworms, etc., exchange O_2 with CO_2 by simple diffusion over their entire body surface. Earthworms use their moist cuticle and insects have a network of tubes (tracheal tubes) to transport atmospheric air within the body. Special vascularised structures called **gills** (branchial respiration) are used by most of the aquatic arthropods and molluscs whereas vascularised bags called **lungs** (pulmonary respiration) are used by the terrestrial forms for the exchange of gases. Among vertebrates, fishes use gills whereas amphibians, reptiles, birds and mammals respire through lungs. Amphibians like frogs can respire through their moist skin (cutaneous respiration) also.

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14.1.1 Human Respiratory System

We have a pair of external nostrils opening out above the upper lips. It leads to a nasal chamber through the nasal passage. The nasal chamber opens into the **pharynx**, a portion of which is the common passage for food and air. The pharynx opens through the larynx region into the **trachea**. Larynx is a cartilaginous box which helps in sound production and hence called the **sound box**. During swallowing glottis can be covered by a thin elastic cartilaginous flap called epiglottis to prevent the entry of food into the larynx. Trachea is a straight tube extending up to the mid-thoracic cavity, which divides at the level of 5th thoracic vertebra into a right and left primary **bronchi**. Each bronchi undergoes repeated divisions to form the secondary and tertiary bronchi and bronchioles ending up in very thin terminal **bronchioles**. The tracheae, primary, secondary and tertiary bronchi, and initial bronchioles are supported by incomplete cartilaginous rings. Each terminal bronchiole gives rise to a number of very thin, irregular-walled and vascularised bag-like structures called **alveoli**. The branching network of bronchi, bronchioles and alveoli comprise the lungs (Figure 14.1). We have two lungs which are covered by a double layered pleura, with pleural fluid between them. It reduces friction on the lung-surface. The outer pleural membrane is in close contact with the thoracic

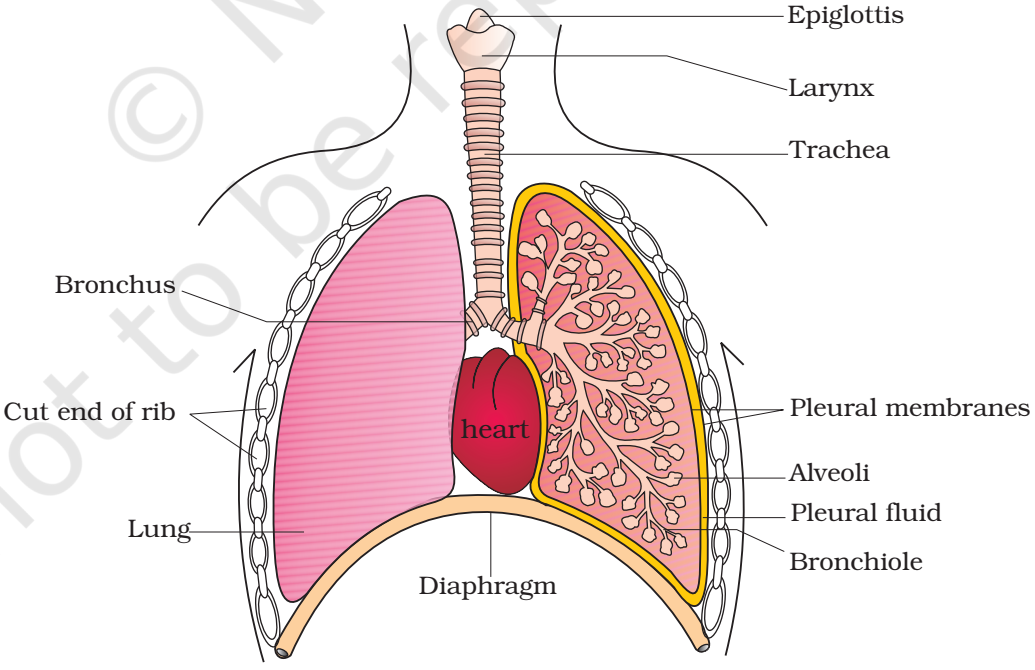

Figure 14.1 Diagrammatic view of human respiratory system (sectional view of the left lung is also shown)

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lining whereas the inner pleural membrane is in contact with the lung surface. The part starting with the external nostrils up to the terminal bronchioles constitute the conducting part whereas the alveoli and their ducts form the respiratory or exchange part of the respiratory system. The conducting part transports the atmospheric air to the alveoli, clears it from foreign particles, humidifies and also brings the air to body temperature. Exchange part is the site of actual diffusion of O_2 and CO_2 between blood and atmospheric air.

The lungs are situated in the thoracic chamber which is anatomically an air-tight chamber. The thoracic chamber is formed dorsally by the vertebral column, ventrally by the sternum, laterally by the ribs and on the lower side by the dome-shaped diaphragm. The anatomical setup of lungs in thorax is such that any change in the volume of the thoracic cavity will be reflected in the lung (pulmonary) cavity. Such an arrangement is essential for breathing, as we cannot directly alter the pulmonary volume.

Respiration involves the following steps:

(i) Breathing or pulmonary ventilation by which atmospheric air is drawn in and CO_2 rich alveolar air is released out.

(ii) Diffusion of gases (O_2 and CO_2) across alveolar membrane.

(iii) Transport of gases by the blood.

(iv) Diffusion of O_2 and CO_2 between blood and tissues.

(v) Utilisation of O_2 by the cells for catabolic reactions and resultant release of CO_2 (cellular respiration as dealt in the Chapter 12).

14.2 MECHANISM OF BREATHING

Breathing involves two stages : **inspiration** during which atmospheric air is drawn in and **expiration** by which the alveolar air is released out. The movement of air into and out of the lungs is carried out by creating a pressure gradient between the lungs and the atmosphere. Inspiration can occur if the pressure within the lungs (intra-pulmonary pressure) is less than the atmospheric pressure, i.e., there is a negative pressure in the lungs with respect to atmospheric pressure. Similarly, expiration takes place when the intra-pulmonary pressure is higher than the atmospheric pressure. The diaphragm and a specialised set of muscles – external and internal intercostals between the ribs, help in generation of such gradients. Inspiration is initiated by the contraction of diaphragm which increases the volume of thoracic chamber in the antero-posterior axis. The contraction of external inter-costal muscles lifts up the ribs and the

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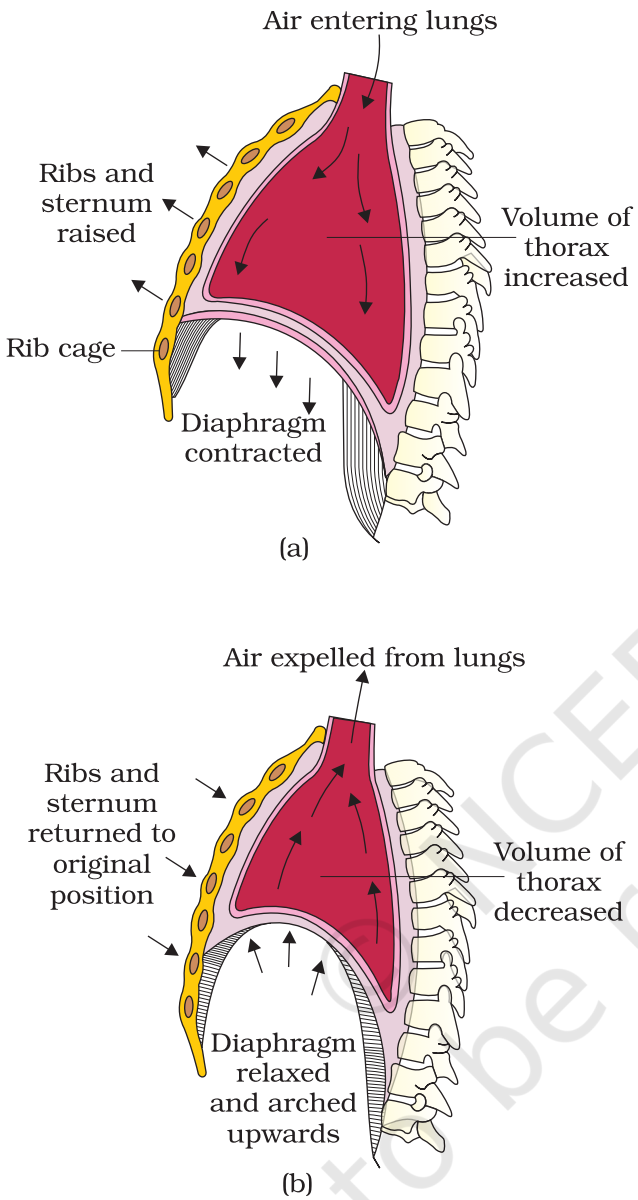

Figure 14.2 Mechanism of breathing showing : (a) inspiration (b) expiration

sternum causing an increase in the volume of the thoracic chamber in the dorso-ventral axis. The overall increase in the thoracic volume causes a similar increase in pulmonary volume. An increase in pulmonary volume decreases the intra-pulmonary pressure to less than the atmospheric pressure which forces the air from outside to move into the lungs, i.e., inspiration (Figure 14.2a). Relaxation of the diaphragm and the inter-costal muscles returns the diaphragm and sternum to their normal positions and reduce the thoracic volume and thereby the pulmonary volume. This leads to an increase in intra-pulmonary pressure to slightly above the atmospheric pressure causing the expulsion of air from the lungs, i.e., expiration (Figure 14.2b). We have the ability to increase the strength of inspiration and expiration with the help of additional muscles in the abdomen. On an average, a healthy human breathes 12-16 times/minute. The volume of air involved in breathing movements can be estimated by using a spirometer which helps in clinical assessment of pulmonary functions.

14.2.1 Respiratory Volumes and Capacities

Tidal Volume (TV): Volume of air inspired or expired during a normal respiration. It is approx. 500 mL., i.e., a healthy man can inspire or expire approximately 6000 to 8000 mL of air per minute.

Inspiratory Reserve Volume (IRV): A person can inspire by a forcible inspiration. This averages 2500 mL to 3000 mL.

Expiratory Reserve Volume (ERV): A person can expire by a forcible expiration. This averages 1000 mL to 1100 mL.

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Residual Volume (RV): Volume of air remaining in the lungs even after a forcible expiration. This averages 1100 mL to 1200 mL.

By adding up a few respiratory volumes described above, one can derive various pulmonary capacities, which can be used in clinical diagnosis.

Inspiratory Capacity (IC): Total volume of air a person can inspire after a normal expiration. This includes tidal volume and inspiratory reserve volume (TV+IRV).

Expiratory Capacity (EC): Total volume of air a person can expire after a normal inspiration. This includes tidal volume and expiratory reserve volume (TV+ERV).

Functional Residual Capacity (FRC): Volume of air that will remain in the lungs after a normal expiration. This includes ERV+RV.

Vital Capacity (VC): The maximum volume of air a person can breathe in after a forced expiration. This includes ERV, TV and IRV or the maximum volume of air a person can breathe out after a forced inspiration.

Total Lung Capacity (TLC): Total volume of air accommodated in the lungs at the end of a forced inspiration. This includes RV, ERV, TV and IRV or vital capacity + residual volume.

14.3 EXCHANGE OF GASES

Alveoli are the primary sites of exchange of gases. Exchange of gases also occur between blood and tissues. O_2 and CO_2 are exchanged in these sites by simple diffusion mainly based on pressure/concentration gradient. Solubility of the gases as well as the thickness of the membranes involved in diffusion are also some important factors that can affect the rate of diffusion.

Pressure contributed by an individual gas in a mixture of gases is called partial pressure and is represented as pO_2 for oxygen and pCO_2 for carbon dioxide. Partial pressures of these two gases in the atmospheric air and the two sites of diffusion are given in Table 14.1 and in Figure 14.3. The data given in the table clearly indicates a concentration gradient for oxygen from alveoli to blood and blood to tissues. Similarly,

TABLE 14.1 Partial Pressures (in mm Hg) of Oxygen and Carbon dioxide at Different Parts Involved in Diffusion in Comparison to those in Atmosphere

Respiratory Gas	Atmospheric Air	Alveoli	Blood (Deoxygenated)	Blood (Oxygenated)	Tissues
O_2	159	104	40	95	40
CO_2	0.3	40	45	40	45

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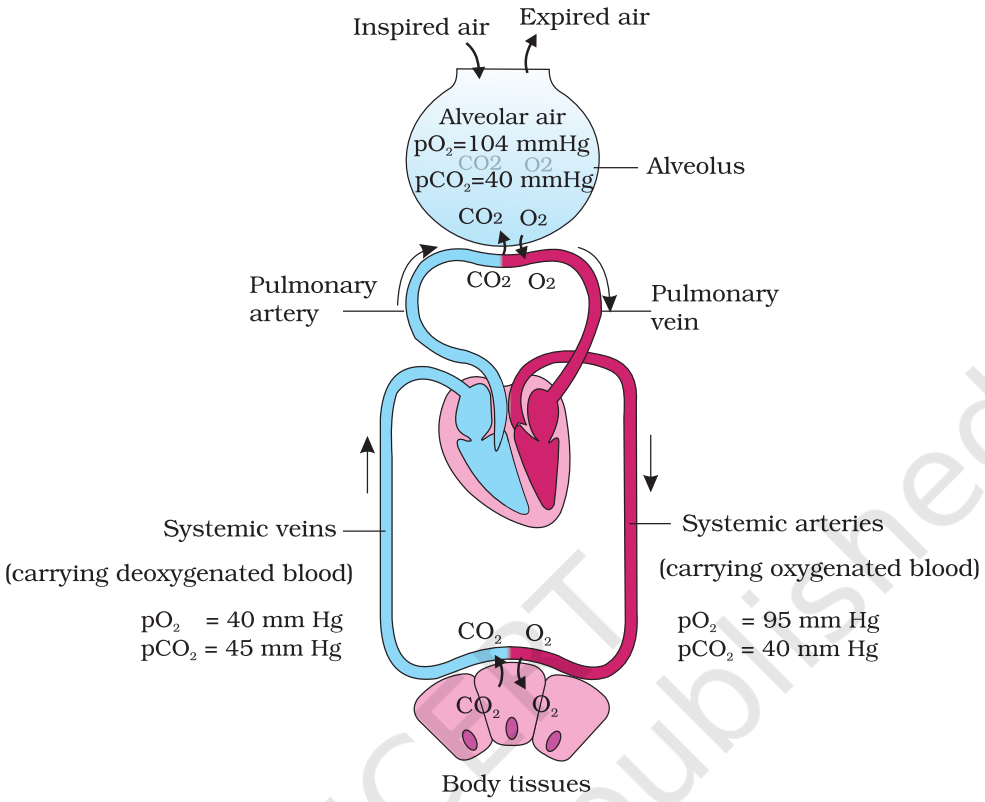

Figure 14.3 Diagrammatic representation of exchange of gases at the alveolus and the body tissues with blood and transport of oxygen and carbon dioxide

a gradient is present for CO_2 in the opposite direction, i.e., from tissues to blood and blood to alveoli. As the solubility of CO_2 is 20-25 times higher than that of O_2, the amount of CO_2 that can diffuse through the diffusion membrane per unit difference in partial pressure is much higher compared to that of O_2. The diffusion membrane is made up of three major layers (Figure 14.4) namely, the thin squamous epithelium of alveoli, the endothelium of alveolar capillaries and the basement substance (composed of a thin basement membrane supporting the squamous epithelium and the basement membrane surrounding the single layer endothelial cells of capillaries) in between them. However, its total thickness is much less than a millimetre. Therefore, all the factors in our body are favourable for diffusion of O_2 from alveoli to tissues and that of CO_2 from tissues to alveoli.

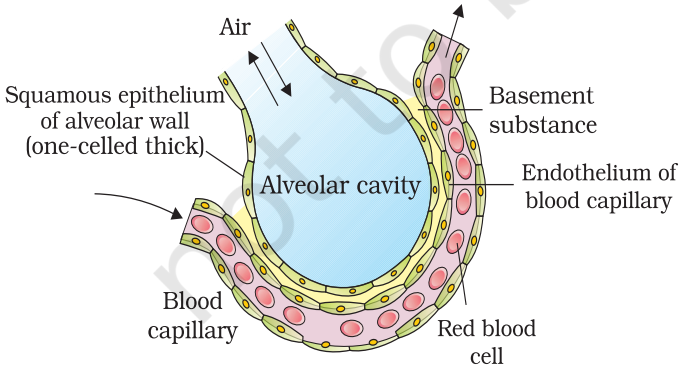

Figure 14.4 A Diagram of a section of an alveolus with a pulmonary capillary.

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14.4 TRANSPORT OF GASES

Blood is the medium of transport for O_2 and CO_2. About 97 per cent of O_2 is transported by RBCs in the blood. The remaining 3 per cent of O_2 is carried in a dissolved state through the plasma. Nearly 20-25 per cent of CO_2 is transported by RBCs whereas 70 per cent of it is carried as bicarbonate. About 7 per cent of CO_2 is carried in a dissolved state through plasma.

14.4.1 Transport of Oxygen

Haemoglobin is a red coloured iron containing pigment present in the RBCs. O_2 can bind with haemoglobin in a reversible manner to form **oxyhaemoglobin**. Each haemoglobin molecule can carry a maximum of four molecules of O_2. Binding of oxygen with haemoglobin is primarily related to partial pressure of O_2. Partial pressure of CO_2, hydrogen ion concentration and temperature are the other factors which can interfere with this binding. A sigmoid curve is obtained when percentage saturation of haemoglobin with O_2 is plotted against the pO_2. This curve is called the Oxygen dissociation curve (Figure 14.5) and is highly useful in studying the effect of factors like pCO_2, H^+ concentration, etc., on binding of O_2 with haemoglobin. In the alveoli, where there is high pO_2, low pCO_2, lesser H^+ concentration and lower temperature, the factors are all favourable for the formation of oxyhaemoglobin, whereas in the tissues, where low pO_2, high pCO_2, high H^+ concentration and higher temperature exist, the conditions are favourable for dissociation of oxygen from the oxyhaemoglobin. This clearly indicates that O_2 gets bound to haemoglobin in the lung surface and gets dissociated at the tissues. Every 100 ml of oxygenated blood can deliver around 5 ml of O_2 to the tissues under normal physiological conditions.

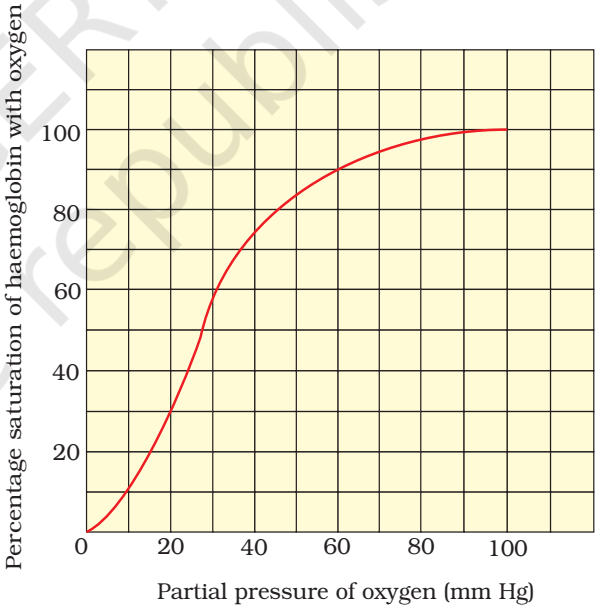

Figure 14.5 Oxygen dissociation curve

14.4.2 Transport of Carbon dioxide

CO_2 is carried by haemoglobin as **carbamino-haemoglobin** (about 20-25 per cent). This binding is related to the partial pressure of CO_2. pO_2 is a major factor which could affect this binding. When pCO_2 is high and pO_2 is low as in the tissues, more binding of carbon dioxide occurs whereas, when the pCO_2 is low and pO_2 is high as in the alveoli, dissociation

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of CO_2 from carbamino-haemoglobin takes place, i.e., CO_2 which is bound to haemoglobin from the tissues is delivered at the alveoli. RBCs contain a very high concentration of the enzyme, carbonic anhydrase and minute quantities of the same is present in the plasma too. This enzyme facilitates the following reaction in both directions.

$$CO_2 + H_2O \underset{}{\overset{\text{Carbonic anhydrase}}{\rightleftharpoons}} H_2CO_3 \overset{\text{Carbonic anhydrase}}{\rightleftharpoons} HCO_3^- + H^+$$

At the tissue site where partial pressure of CO_2 is high due to catabolism, CO_2 diffuses into blood (RBCs and plasma) and forms HCO_3^- and H^+. At the alveolar site where pCO_2 is low, the reaction proceeds in the opposite direction leading to the formation of CO_2 and H_2O. Thus, CO_2 trapped as bicarbonate at the tissue level and transported to the alveoli is released out as CO_2 (Figure 14.4). Every 100 ml of deoxygenated blood delivers approximately 4 ml of CO_2 to the alveoli.

14.5 Regulation of Respiration

Human beings have a significant ability to maintain and moderate the respiratory rhythm to suit the demands of the body tissues. This is done by the neural system. A specialised centre present in the medulla region of the brain called respiratory rhythm centre is primarily responsible for this regulation. Another centre present in the pons region of the brain called pneumotaxic centre can moderate the functions of the respiratory rhythm centre. Neural signal from this centre can reduce the duration of inspiration and thereby alter the respiratory rate. A chemosensitive area is situated adjacent to the rhythm centre which is highly sensitive to CO_2 and hydrogen ions. Increase in these substances can activate this centre, which in turn can signal the rhythm centre to make necessary adjustments in the respiratory process by which these substances can be eliminated. Receptors associated with aortic arch and carotid artery also can recognise changes in CO_2 and H^+ concentration and send necessary signals to the rhythm centre for remedial actions. The role of oxygen in the regulation of respiratory rhythm is quite insignificant.

14.6 Disorders of Respiratory System

Asthma is a difficulty in breathing causing wheezing due to inflammation of bronchi and bronchioles.

Emphysema is a chronic disorder in which alveolar walls are damaged due to which respiratory surface is decreased. One of the major causes of this is cigarette smoking.

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Occupational Respiratory Disorders: In certain industries, especially those involving grinding or stone-breaking, so much dust is produced that the defense mechanism of the body cannot fully cope with the situation. Long exposure can give rise to inflammation leading to fibrosis (proliferation of fibrous tissues) and thus causing serious lung damage. Workers in such industries should wear protective masks.

Summary

Cells utilise oxygen for metabolism and produce energy along with substances like carbon dioxide which is harmful. Animals have evolved different mechanisms for the transport of oxygen to the cells and for the removal of carbon dioxide from there. We have a well developed respiratory system comprising two lungs and associated air passages to perform this function.

The first step in respiration is breathing by which atmospheric air is taken in (inspiration) and the alveolar air is released out (expiration). Exchange of O_2 and CO_2 between deoxygenated blood and alveoli, transport of these gases throughout the body by blood, exchange of O_2 and CO_2 between the oxygenated blood and tissues and utilisation of O_2 by the cells (cellular respiration) are the other steps involved.

Inspiration and expiration are carried out by creating pressure gradients between the atmosphere and the alveoli with the help of specialised muscles – intercostals and diaphragm. Volumes of air involved in these activities can be estimated with the help of spirometer and are of clinical significance.

Exchange of O_2 and CO_2 at the alveoli and tissues occur by diffusion. Rate of diffusion is dependent on the partial pressure gradients of O_2 (pO_2) and CO_2 (pCO_2), their solubility as well as the thickness of the diffusion surface. These factors in our body facilitate diffusion of O_2 from the alveoli to the deoxygenated blood as well as from the oxygenated blood to the tissues. The factors are favourable for the diffusion of CO_2 in the opposite direction, i.e., from tissues to alveoli.

Oxygen is transported mainly as oxyhaemoglobin. In the alveoli where pO_2 is higher, O_2 gets bound to haemoglobin which is easily dissociated at the tissues where pO_2 is low and pCO_2 and H^+ concentration are high. Nearly 70 per cent of carbon dioxide is transported as bicarbonate (HCO_3^-) with the help of the enzyme carbonic anhydrase. 20-25 per cent of carbon dioxide is carried by haemoglobin as carbamino-haemoglobin. In the tissues where pCO_2 is high, it gets bound to blood whereas in the alveoli where pCO_2 is low and pO_2 is high, it gets removed from the blood.

Respiratory rhythm is maintained by the respiratory centre in the medulla region of brain. A pneumotaxic centre in the pons region of the brain and a chemosensitive area in the medulla can alter respiratory mechanism.

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EXERCISES

1. Define vital capacity. What is its significance?
2. State the volume of air remaining in the lungs after a normal breathing.
3. Diffusion of gases occurs in the alveolar region only and not in the other parts of respiratory system. Why?
4. What are the major transport mechanisms for CO_2? Explain.
5. What will be the pO_2 and pCO_2 in the atmospheric air compared to those in the alveolar air ?
   (i) pO_2 lesser, pCO_2 higher
   (ii) pO_2 higher, pCO_2 lesser
   (iii) pO_2 higher, pCO_2 higher
   (iv) pO_2 lesser, pCO_2 lesser
6. Explain the process of inspiration under normal conditions.
7. How is respiration regulated?
8. What is the effect of pCO_2 on oxygen transport?
9. What happens to the respiratory process in a man going up a hill?
10. What is the site of gaseous exchange in an insect?
11. Define oxygen dissociation curve. Can you suggest any reason for its sigmoidal pattern?
12. Have you heard about hypoxia? Try to gather information about it, and discuss with your friends.
13. Distinguish between
    (a) IRV and ERV
    (b) Inspiratory capacity and Expiratory capacity.
    (c) Vital capacity and Total lung capacity.
14. What is Tidal volume? Find out the Tidal volume (approximate value) for a healthy human in an hour.

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Chapter 15
Body Fluids and Circulation

15.1 *Blood*

15.2 *Lymph (Tissue Fluid)*

15.3 *Circulatory Pathways*

15.4 *Double Circulation*

15.5 *Regulation of Cardiac Activity*

15.6 *Disorders of Circulatory System*

You have learnt that all living cells have to be provided with nutrients, O_2 and other essential substances. Also, the waste or harmful substances produced, have to be removed continuously for healthy functioning of tissues. It is therefore, essential to have efficient mechanisms for the movement of these substances to the cells and from the cells. Different groups of animals have evolved different methods for this transport. Simple organisms like sponges and coelenterates circulate water from their surroundings through their body cavities to facilitate the cells to exchange these substances. More complex organisms use special fluids within their bodies to transport such materials. **Blood** is the most commonly used body fluid by most of the higher organisms, including humans, for this purpose. Another body fluid, **lymph,** also helps in the transport of certain substances. In this chapter, you will learn about the composition and properties of blood and lymph (tissue fluid) and the mechanism of circulation of blood is also explained herein.

15.1 Blood

Blood is a special connective tissue consisting of a fluid matrix, plasma, and formed elements.

15.1.1 Plasma

Plasma is a straw coloured, viscous fluid constituting nearly 55 per cent of the blood. 90-92 per cent of plasma is water and proteins contribute 6-8 per cent of it. Fibrinogen, globulins and albumins are the major proteins.

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Fibrinogens are needed for clotting or coagulation of blood. Globulins primarily are involved in defense mechanisms of the body and the albumins help in osmotic balance. Plasma also contains small amounts of minerals like Na^+, Ca^{++}, Mg^{++}, HCO_3^-, Cl^-, etc. Glucose, amino acids, lipids, etc., are also present in the plasma as they are always in transit in the body. Factors for coagulation or clotting of blood are also present in the plasma in an inactive form. Plasma without the clotting factors is called serum.

15.1.2 Formed Elements

Erythrocytes, leucocytes and platelets are collectively called formed elements (Figure 15.1) and they constitute nearly 45 per cent of the blood.

Erythrocytes or red blood cells (RBC) are the most abundant of all the cells in blood. A healthy adult man has, on an average, 5 millions to 5.5 millions of RBCs mm^{-3} of blood. RBCs are formed in the red bone marrow in the adults. RBCs are devoid of nucleus in most of the mammals and are biconcave in shape. They have a red coloured, iron containing complex protein called haemoglobin, hence the colour and name of these cells. A healthy individual has 12-16 gms of haemoglobin in every 100 ml of blood. These molecules play a significant role in transport of respiratory gases. RBCs have an average life span of 120 days after which they are destroyed in the spleen (graveyard of RBCs).

Leucocytes are also known as white blood cells (WBC) as they are colourless due to the lack of haemoglobin. They are nucleated and are relatively lesser in number which averages 6000-8000 mm^{-3} of blood. Leucocytes are generally short lived. We have two main categories of WBCs – granulocytes and agranulocytes. Neutrophils, eosinophils and basophils are different types of granulocytes, while lymphocytes and monocytes are the agranulocytes. Neutrophils are the most abundant cells (60-65 per cent) of the total WBCs and basophils are the least (0.5-1 per cent) among them. Neutrophils and monocytes (6-8 per cent) are phagocytic cells which destroy foreign organisms entering the body. Basophils secrete histamine, serotonin, heparin, etc., and are involved in inflammatory reactions. Eosinophils (2-3 per cent) resist infections and are also

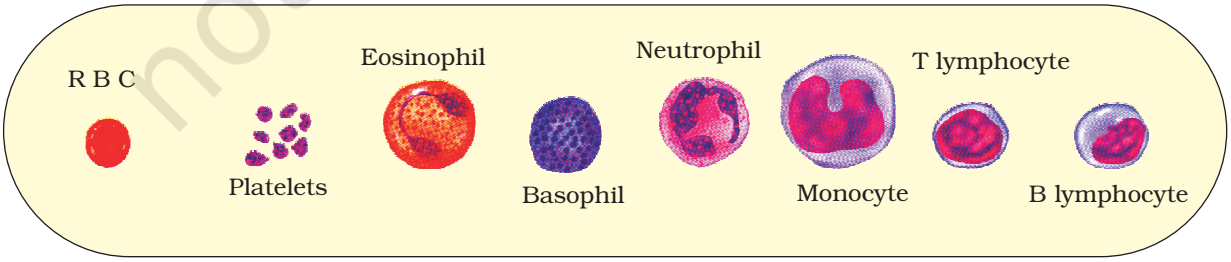

Figure 15.1 Diagrammatic representation of formed elements in blood

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associated with allergic reactions. Lymphocytes (20-25 per cent) are of two major types – 'B' and 'T' forms. Both B and T lymphocytes are responsible for immune responses of the body.

Platelets also called **thrombocytes**, are cell fragments produced from megakaryocytes (special cells in the bone marrow). Blood normally contains 1,500,00-3,500,00 platelets mm^{-3}. Platelets can release a variety of substances most of which are involved in the coagulation or clotting of blood. A reduction in their number can lead to clotting disorders which will lead to excessive loss of blood from the body.

15.1.3 Blood Groups

As you know, blood of human beings differ in certain aspects though it appears to be similar. Various types of grouping of blood has been done. Two such groupings – the ABO and Rh – are widely used all over the world.

15.1.3.1 ABO grouping

ABO grouping is based on the presence or absence of two surface antigens (chemicals that can induce immune response) on the RBCs namely A and B. Similarly, the plasma of different individuals contain two natural antibodies (proteins produced in response to antigens). The distribution of antigens and antibodies in the four groups of blood, **A, B, AB** and **O** are given in Table 15.1. You probably know that during blood transfusion, any blood cannot be used; the blood of a donor has to be carefully matched with the blood of a recipient before any blood transfusion to avoid severe problems of clumping (destruction of RBC). The donor's compatibility is also shown in the Table 15.1.

Table 15.1 Blood Groups and Donor Compatibility

Blood Group	Antigens on RBCs	Antibodies in Plasma	Donor's Group
A	A	anti-B	A, O
B	B	anti-A	B, O
AB	A, B	nil	AB, A, B, O
O	nil	anti-A, B	O

From the above mentioned table it is evident that group 'O' blood can be donated to persons with any other blood group and hence 'O' group individuals are called 'universal donors'. Persons with 'AB' group can accept blood from persons with AB as well as the other groups of blood. Therefore, such persons are called 'universal recipients'.

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15.1.3.2 Rh grouping

Another antigen, the Rh antigen similar to one present in Rhesus monkeys (hence Rh), is also observed on the surface of RBCs of majority (nearly 80 per cent) of humans. Such individuals are called **Rh positive** (Rh+ve) and those in whom this antigen is absent are called **Rh negative** (Rh-ve). An Rh-ve person, if exposed to Rh+ve blood, will form specific antibodies against the Rh antigens. Therefore, Rh group should also be matched before transfusions. A special case of Rh incompatibility (mismatching) has been observed between the Rh-ve blood of a pregnant mother with Rh+ve blood of the foetus. Rh antigens of the foetus do not get exposed to the Rh-ve blood of the mother in the first pregnancy as the two bloods are well separated by the placenta. However, during the delivery of the first child, there is a possibility of exposure of the maternal blood to small amounts of the Rh+ve blood from the foetus. In such cases, the mother starts preparing antibodies against Rh antigen in her blood. In case of her subsequent pregnancies, the Rh antibodies from the mother (Rh-ve) can leak into the blood of the foetus (Rh+ve) and destroy the foetal RBCs. This could be fatal to the foetus or could cause severe anaemia and jaundice to the baby. This condition is called *erythroblastosis foetalis*. This can be avoided by administering anti-Rh antibodies to the mother immediately after the delivery of the first child.

15.1.4 Coagulation of Blood

You know that when you cut your finger or hurt yourself, your wound does not continue to bleed for a long time; usually the blood stops flowing after sometime. *Do you know why?* Blood exhibits coagulation or clotting in response to an injury or trauma. This is a mechanism to prevent excessive loss of blood from the body. You would have observed a dark reddish brown scum formed at the site of a cut or an injury over a period of time. It is a clot or coagulam formed mainly of a network of threads called fibrins in which dead and damaged formed elements of blood are trapped. Fibrins are formed by the conversion of inactive fibrinogens in the plasma by the enzyme thrombin. Thrombins, in turn are formed from another inactive substance present in the plasma called prothrombin. An enzyme complex, thrombokinase, is required for the above reaction. This complex is formed by a series of linked enzymic reactions (cascade process) involving a number of factors present in the plasma in an inactive state. An injury or a trauma stimulates the platelets in the blood to release certain factors which activate the mechanism of coagulation. Certain factors released by the tissues at the site of injury also can initiate coagulation. Calcium ions play a very important role in clotting.

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15.2 Lymph (Tissue Fluid)

As the blood passes through the capillaries in tissues, some water along with many small water soluble substances move out into the spaces between the cells of tissues leaving the larger proteins and most of the formed elements in the blood vessels. This fluid released out is called the interstitial fluid or tissue fluid. It has the same mineral distribution as that in plasma. Exchange of nutrients, gases, etc., between the blood and the cells always occur through this fluid. An elaborate network of vessels called the lymphatic system collects this fluid and drains it back to the major veins. The fluid present in the lymphatic system is called the lymph. Lymph is a colourless fluid containing specialised lymphocytes which are responsible for the immune responses of the body. Lymph is also an important carrier for nutrients, hormones, etc. Fats are absorbed through lymph in the lacteals present in the intestinal villi.

15.3 Circulatory Pathways

The circulatory patterns are of two types – open or closed. **Open circulatory system** is present in arthropods and molluscs in which blood pumped by the heart passes through large vessels into open spaces or body cavities called sinuses. Annelids and chordates have a **closed circulatory system** in which the blood pumped by the heart is always circulated through a closed network of blood vessels. This pattern is considered to be more advantageous as the flow of fluid can be more precisely regulated.

All vertebrates possess a muscular chambered heart. Fishes have a 2-chambered heart with an atrium and a ventricle. Amphibians and the reptiles (except crocodiles) have a 3-chambered heart with two atria and a single ventricle, whereas crocodiles, birds and mammals possess a 4-chambered heart with two atria and two ventricles. In fishes the heart pumps out deoxygenated blood which is oxygenated by the gills and supplied to the body parts from where deoxygenated blood is returned to the heart (single circulation). In amphibians and reptiles, the left atrium receives oxygenated blood from the gills/lungs/skin and the right atrium gets the deoxygenated blood from other body parts. However, they get mixed up in the single ventricle which pumps out mixed blood (incomplete double circulation). In birds and mammals, oxygenated and deoxygenated blood received by the left and right atria respectively passes on to the ventricles of the same sides. The ventricles pump it out without any mixing up, i.e., two separate circulatory pathways are present in these organisms, hence, these animals have double circulation. Let us study the human circulatory system.

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15.3.1 Human Circulatory System

Human circulatory system, also called the blood vascular system consists of a muscular chambered heart, a network of closed branching blood vessels and blood, the fluid which is circulated.

Heart, the mesodermally derived organ, is situated in the thoracic cavity, in between the two lungs, slightly tilted to the left. It has the size of a clenched fist. It is protected by a double walled membranous bag, **pericardium,** enclosing the pericardial fluid. Our heart has four chambers, two relatively small upper chambers called **atria** and two larger lower chambers called **ventricles**. A thin, muscular wall called the inter-atrial septum separates the right and the left atria, whereas a thick-walled, the inter-ventricular septum, separates the left and the right ventricles (Figure 15.2). The atrium and the ventricle of the same side are also separated by a thick fibrous tissue called the atrio-ventricular septum. However, each of these septa are provided with an opening through which the two chambers of the same side are connected. The opening between the right atrium and the right ventricle is guarded by a valve formed of three muscular flaps or cusps, the tricuspid valve, whereas a bicuspid or mitral valve guards the opening between the left atrium and the left ventricle. The openings of the right and the left ventricles into the

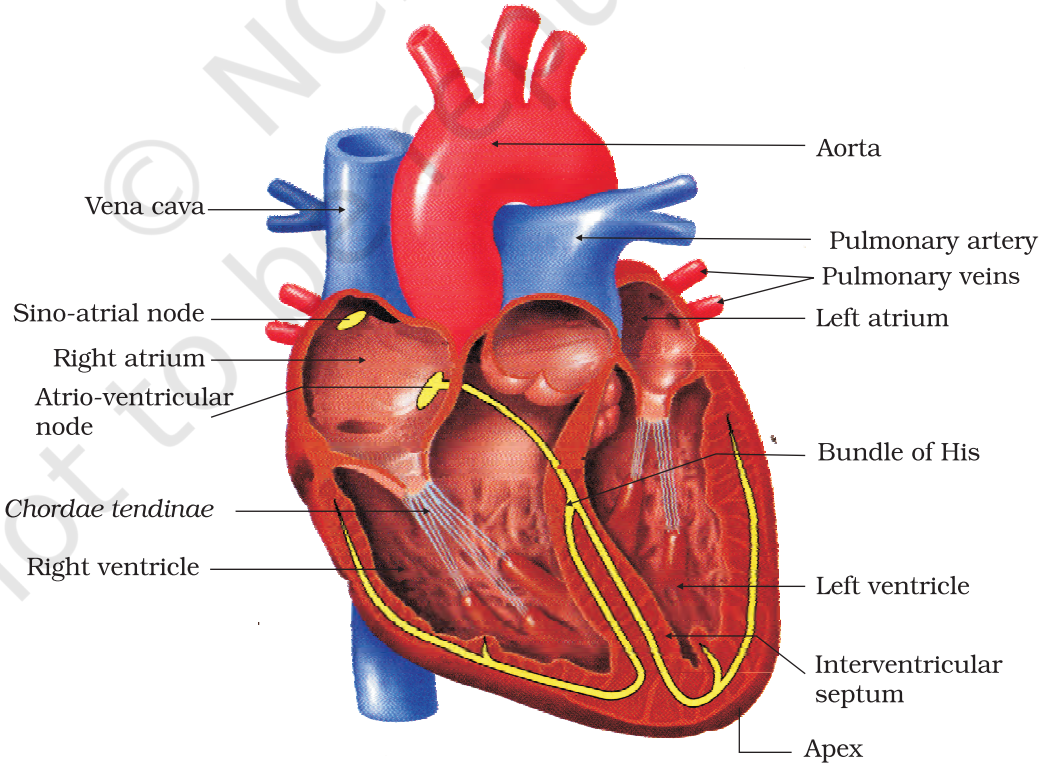

Figure 15.2 Section of a human heart

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pulmonary artery and the aorta respectively are provided with the semilunar valves. The valves in the heart allows the flow of blood only in one direction, i.e., from the atria to the ventricles and from the ventricles to the pulmonary artery or aorta. These valves prevent any backward flow.

The entire heart is made of cardiac muscles. The walls of ventricles are much thicker than that of the atria. A specialised cardiac musculature called the nodal tissue is also distributed in the heart (Figure 15.2). A patch of this tissue is present in the right upper corner of the right atrium called the **sino-atrial node** (SAN). Another mass of this tissue is seen in the lower left corner of the right atrium close to the atrio-ventricular septum called the **atrio-ventricular node** (AVN). A bundle of nodal fibres, atrio-ventricular bundle (AV bundle) continues from the AVN which passes through the atrio-ventricular septa to emerge on the top of the inter-ventricular septum and immediately divides into a right and left bundle. These branches give rise to minute fibres throughout the ventricular musculature of the respective sides and are called purkinje fibres. The nodal musculature has the ability to generate action potentials without any external stimuli, i.e., it is autoexcitable. However, the number of action potentials that could be generated in a minute vary at different parts of the nodal system. The SAN can generate the maximum number of action potentials, i.e., 70-75 min^{-1}, and is responsible for initiating and maintaining the rhythmic contractile activity of the heart. Therefore, it is called the pacemaker. Our heart normally beats 70-75 times in a minute (average 72 beats min^{-1}).

15.3.2 Cardiac Cycle

How does the heart function? Let us take a look. To begin with, all the four chambers of heart are in a relaxed state, i.e., they are in joint diastole. As the tricuspid and bicuspid valves are open, blood from the pulmonary veins and vena cava flows into the left and the right ventricle respectively through the left and right atria. The semilunar valves are closed at this stage. The SAN now generates an action potential which stimulates both the atria to undergo a simultaneous contraction – the atrial systole. This increases the flow of blood into the ventricles by about 30 per cent. The action potential is conducted to the ventricular side by the AVN and AV bundle from where the bundle of His transmits it through the entire ventricular musculature. This causes the ventricular muscles to contract, (ventricular systole), the atria undergoes relaxation (diastole), coinciding with the ventricular systole. Ventricular systole increases the ventricular pressure causing the closure of tricuspid and

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bicuspid valves due to attempted backflow of blood into the atria. As the ventricular pressure increases further, the semilunar valves guarding the pulmonary artery (right side) and the aorta (left side) are forced open, allowing the blood in the ventricles to flow through these vessels into the circulatory pathways. The ventricles now relax (ventricular diastole) and the ventricular pressure falls causing the closure of semilunar valves which prevents the backflow of blood into the ventricles. As the ventricular pressure declines further, the tricuspid and bicuspid valves are pushed open by the pressure in the atria exerted by the blood which was being emptied into them by the veins. The blood now once again moves freely to the ventricles. The ventricles and atria are now again in a relaxed (joint diastole) state, as earlier. Soon the SAN generates a new action potential and the events described above are repeated in that sequence and the process continues.

This sequential event in the heart which is cyclically repeated is called the cardiac cycle and it consists of systole and diastole of both the atria and ventricles. As mentioned earlier, the heart beats 72 times per minute, i.e., that many cardiac cycles are performed per minute. From this it could be deduced that the duration of a cardiac cycle is 0.8 seconds. During a cardiac cycle, each ventricle pumps out approximately 70 mL of blood which is called the stroke volume. The stroke volume multiplied by the heart rate (no. of beats per min.) gives the cardiac output. Therefore, the cardiac output can be defined as the volume of blood pumped out by each ventricle per minute and averages 5000 mL or 5 litres in a healthy individual. The body has the ability to alter the stroke volume as well as the heart rate and thereby the cardiac output. For example, the cardiac output of an athlete will be much higher than that of an ordinary man.

During each cardiac cycle two prominent sounds are produced which can be easily heard through a stethoscope. The first heart sound (lub) is associated with the closure of the tricuspid and bicuspid valves whereas the second heart sound (dub) is associated with the closure of the semilunar valves. These sounds are of clinical diagnostic significance.

15.3.3 Electrocardiogram (ECG)

You are probably familiar with this scene from a typical hospital television show: A patient is hooked up to a monitoring machine that shows voltage traces on a screen and makes the sound "... pip... pip... pip..... peeeeeeeeeeeeeeeeeeeeee" as the patient goes into cardiac arrest. This type of machine (electro-cardiograph) is used to obtain an electrocardiogram (ECG). ECG is a graphical representation of the electrical activity of the heart during a cardiac cycle. To obtain a standard ECG (as shown in the

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Figure 15.3), a patient is connected to the machine with three electrical leads (one to each wrist and to the left ankle) that continuously monitor the heart activity. For a detailed evaluation of the heart's function, multiple leads are attached to the chest region. Here, we will talk only about a standard ECG.

Each peak in the ECG is identified with a letter from P to T that corresponds to a specific electrical activity of the heart.

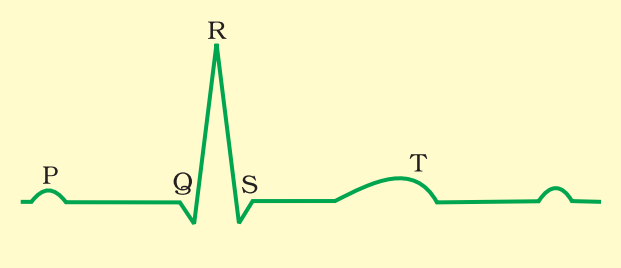

Figure 15.3 Diagrammatic presentation of a standard ECG

The P-wave represents the electrical **excitation (or depolarisation) of the atria**, which leads to the contraction of both the atria.

The QRS complex represents the **depolarisation of the ventricles**, which initiates the ventricular contraction. The contraction starts shortly after Q and marks the beginning of the systole.

The T-wave represents the return of the ventricles from excited to normal state (**repolarisation**). The end of the T-wave marks the end of systole.

Obviously, by counting the number of QRS complexes that occur in a given time period, one can determine the heart beat rate of an individual. Since the ECGs obtained from different individuals have roughly the same shape for a given lead configuration, any deviation from this shape indicates a possible abnormality or disease. Hence, it is of a great clinical significance.

15.4 DOUBLE CIRCULATION

The blood flows strictly by a fixed route through **Blood Vessels**—the arteries and veins. Basically, each artery and vein consists of three layers: an inner lining of squamous endothelium, the **tunica intima**, a middle layer of smooth muscle and elastic fibres, the **tunica media,** and an external layer of fibrous connective tissue with collagen fibres, the **tunica externa**. The tunica media is comparatively thin in the veins (Figure 15.4).

As mentioned earlier, the blood pumped by the right ventricle enters the pulmonary artery, whereas the left ventricle pumps blood into the aorta. The deoxygenated blood pumped into the pulmonary artery is passed on to the lungs from where the oxygenated blood is carried by the pulmonary veins into the left atrium. This pathway constitutes the pulmonary circulation. The oxygenated blood entering the aorta is carried by a network of arteries, arterioles and capillaries to the tissues from where the deoxygenated blood is collected by a system of venules, veins and vena cava and emptied into the right atrium. This is the systemic circulation (Figure 15.4). The systemic circulation provides nutrients, O_2 and other essential substances to the tissues and takes CO_2 and other harmful substances away for elimination. A unique vascular connection exists between the digestive tract and liver called

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hepatic portal system. The hepatic portal vein carries blood from intestine to the liver before it is delivered to the systemic circulation. A special coronary system of blood vessels is present in our body exclusively for the circulation of blood to and from the cardiac musculature.

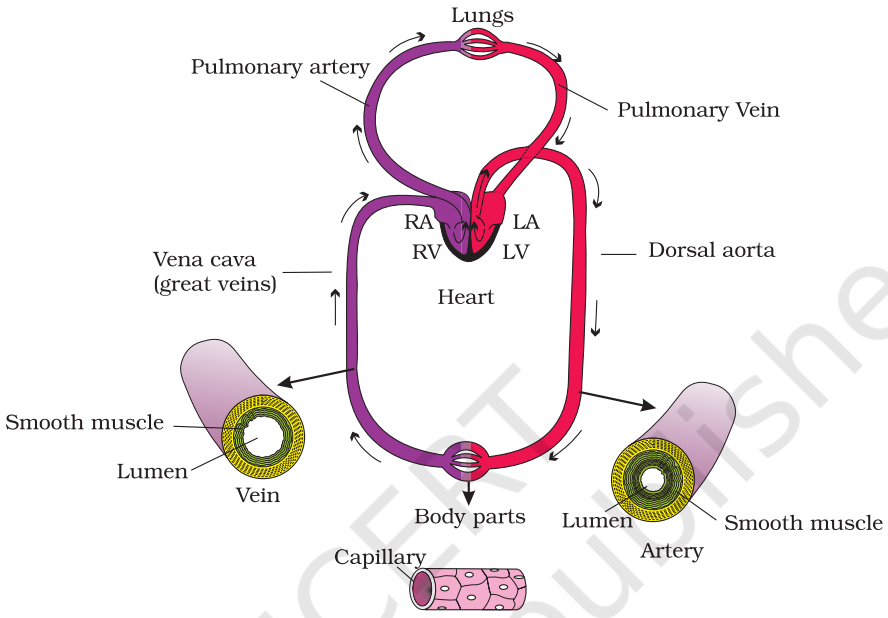

Figure 15.4 Schematic plan of blood circulation in human

15.5 Regulation of Cardiac Activity

Normal activities of the heart are regulated intrinsically, i.e., auto regulated by specialised muscles (nodal tissue), hence the heart is called myogenic. A special neural centre in the medulla oblangata can moderate the cardiac function through autonomic nervous system (ANS). Neural signals through the sympathetic nerves (part of ANS) can increase the rate of heart beat, the strength of ventricular contraction and thereby the cardiac output. On the other hand, parasympathetic neural signals (another component of ANS) decrease the rate of heart beat, speed of conduction of action potential and thereby the cardiac output. Adrenal medullary hormones can also increase the cardiac output.

15.6 Disorders of Circulatory System

High Blood Pressure (Hypertension): Hypertension is the term for blood pressure that is higher than normal (120/80). In this measurement 120 mm Hg (millimetres of mercury pressure) is the systolic, or pumping, pressure and 80 mm Hg is the diastolic, or resting, pressure. If repeated checks of blood pressure of an individual is 140/90 (140 over 90) or

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higher, it shows hypertension. High blood pressure leads to heart diseases and also affects vital organs like brain and kidney.

Coronary Artery Disease (CAD): Coronary Artery Disease, often referred to as **atherosclerosis**, affects the vessels that supply blood to the heart muscle. It is caused by deposits of calcium, fat, cholesterol and fibrous tissues, which makes the lumen of arteries narrower.

Angina: It is also called 'angina pectoris'. A symptom of acute chest pain appears when no enough oxygen is reaching the heart muscle. Angina can occur in men and women of any age but it is more common among the middle-aged and elderly. It occurs due to conditions that affect the blood flow.

Heart Failure: Heart failure means the state of heart when it is not pumping blood effectively enough to meet the needs of the body. It is sometimes called congestive heart failure because congestion of the lungs is one of the main symptoms of this disease. Heart failure is not the same as cardiac arrest (when the heart stops beating) or a heart attack (when the heart muscle is suddenly damaged by an inadequate blood supply).

Summary

Vertebrates circulate blood, a fluid connective tissue, in their body, to transport essential substances to the cells and to carry waste substances from there. Another fluid, lymph (tissue fluid) is also used for the transport of certain substances.

Blood comprises of a fluid matrix, plasma and formed elements. Red blood cells (RBCs, erythrocytes), white blood cells (WBCs, leucocytes) and platelets (thrombocytes) constitute the formed elements. Blood of humans are grouped into A, B, AB and O systems based on the presence or absence of two surface antigens, A, B on the RBCs. Another blood grouping is also done based on the presence or absence of another antigen called Rhesus factor (Rh) on the surface of RBCs. The spaces between cells in the tissues contain a fluid derived from blood called tissue fluid. This fluid called lymph is almost similar to blood except for the protein content and the formed elements.

All vertebrates and a few invertebrates have a closed circulatory system. Our circulatory system consists of a muscular pumping organ, heart, a network of vessels and a fluid, blood. Heart has two atria and two ventricles. Cardiac musculature is auto-excitable. Sino-atrial node (SAN) generates the maximum number of action protentials per minute (70-75/min) and therefore, it sets the pace of the activities of the heart. Hence it is called the Pacemaker. The action potential causes the atria and then the ventricles to undergo contraction (systole) followed by their relaxation (diastole). The systole forces the blood to move from the atria to the ventricles and to the pulmonary artery and the aorta. The cardiac cycle is formed by sequential events in the heart which is cyclically repeated and is called the cardiac cycle. A healthy person shows 72 such cycles per minute. About 70 mL of blood is pumped out by each ventricle during a cardiac cycle and it is called the stroke or beat volume. Volume of blood pumped out by each ventricle of heart per minute is called the cardiac output and it is equal to the product of stroke volume and heart rate (approx 5 litres). The electrical activity of the heart can be recorded from

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the body surface by using electrocardiograph and the recording is called electrocardiogram (ECG) which is of clinical importance.

We have a complete double circulation, i.e., two circulatory pathways, namely, pulmonary and systemic are present. The pulmonary circulation starts by the pumping of deoxygenated blood by the right ventricle which is carried to the lungs where it is oxygenated and returned to the left atrium. The systemic circulation starts with the pumping of oxygenated blood by the left ventricle to the aorta which is carried to all the body tissues and the deoxygenated blood from there is collected by the veins and returned to the right atrium. Though the heart is autoexcitable, its functions can be moderated by neural and hormonal mechanisms.

EXERCISES

1. Name the components of the formed elements in the blood and mention one major function of each of them.
2. What is the importance of plasma proteins?
3. Match Column I with Column II :

Column I	**Column II**
(a) Eosinophils	(i) Coagulation
(b) RBC	(ii) Universal Recipient
(c) AB Group	(iii) Resist Infections
(d) Platelets	(iv) Contraction of Heart
(e) Systole	(v) Gas transport

4. Why do we consider blood as a connective tissue?
5. What is the difference between lymph and blood?
6. What is meant by double circulation? What is its significance?
7. Write the differences between :
   (a) Blood and Lymph
   (b) Open and Closed system of circulation
   (c) Systole and Diastole
   (d) P-wave and T-wave
8. Describe the evolutionary change in the pattern of heart among the vertebrates.
9. Why do we call our heart myogenic?
10. Sino-atrial node is called the pacemaker of our heart. Why?
11. What is the significance of atrio-ventricular node and atrio-ventricular bundle in the functioning of heart?
12. Define a cardiac cycle and the cardiac output.
13. Explain heart sounds.
14. Draw a standard ECG and explain the different segments in it.

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Chapter 16
Excretory Products and their Elimination

16.1 Human Excretory System

16.2 Urine Formation

16.3 Function of the Tubules

16.4 Mechanism of Concentration of the Filtrate

16.5 Regulation of Kidney Function

16.6 Micturition

16.7 Role of other Organs in Excretion

16.8 Disorders of the Excretory System

Animals accumulate ammonia, urea, uric acid, carbon dioxide, water and ions like Na^+, K^+, Cl^-, phosphate, sulphate, etc., either by metabolic activities or by other means like excess ingestion. These substances have to be removed totally or partially. In this chapter, you will learn the mechanisms of elimination of these substances with special emphasis on common nitrogenous wastes. Ammonia, urea and uric acid are the major forms of nitrogenous wastes excreted by the animals. Ammonia is the most toxic form and requires large amount of water for its elimination, whereas uric acid, being the least toxic, can be removed with a minimum loss of water.

The process of excreting ammonia is *Ammonotelism*. Many bony fishes, aquatic amphibians and aquatic insects are ***ammonotelic*** in nature. Ammonia, as it is readily soluble, is generally excreted by diffusion across body surfaces or through gill surfaces (in fish) as ammonium ions. Kidneys do not play any significant role in its removal. Terrestrial adaptation necessitated the production of lesser toxic nitrogenous wastes like urea and uric acid for conservation of water. Mammals, many terrestrial amphibians and marine fishes mainly excrete urea and are called ***ureotelic*** animals. Ammonia produced by metabolism is converted into urea in the liver of these animals and released into the blood which is filtered and excreted out by the kidneys. Some amount of urea may be retained in the kidney matrix of some of these animals to maintain a desired osmolarity. Reptiles, birds, land snails and insects excrete nitrogenous wastes as uric acid in the form of pellet or paste with a minimum loss of water and are called ***uricotelic*** animals.

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A survey of animal kingdom presents a variety of excretory structures. In most of the invertebrates, these structures are simple tubular forms whereas vertebrates have complex tubular organs called kidneys. Some of these structures are mentioned here. Protonephridia or flame cells are the excretory structures in Platyhelminthes (Flatworms, e.g., *Planaria*), rotifers, some annelids and the cephalochordate – *Amphioxus*. Protonephridia are primarily concerned with ionic and fluid volume regulation, i.e., osmoregulation. Nephridia are the tubular excretory structures of earthworms and other annelids. Nephridia help to remove nitrogenous wastes and maintain a fluid and ionic balance. Malpighian tubules are the excretory structures of most of the insects including cockroaches. Malpighian tubules help in the removal of nitrogenous wastes and osmoregulation. Antennal glands or green glands perform the excretory function in crustaceans like prawns.

16.1 HUMAN EXCRETORY SYSTEM

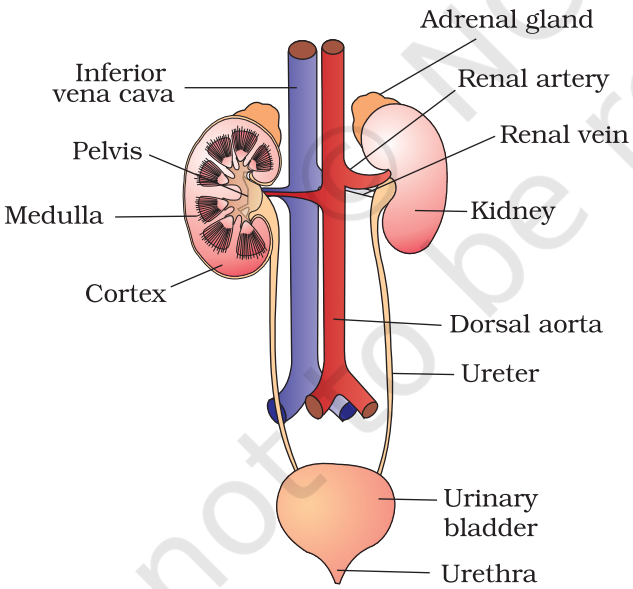

Figure 16.1 Human Urinary system

In humans, the excretory system consists of a pair of kidneys, one pair of ureters, a urinary bladder and a urethra (Figure 16.1). Kidneys are reddish brown, bean shaped structures situated between the levels of last thoracic and third lumbar vertebra close to the dorsal inner wall of the abdominal cavity. Each kidney of an adult human measures 10-12 cm in length, 5-7 cm in width, 2-3 cm in thickness with an average weight of 120-170 g. Towards the centre of the inner concave surface of the kidney is a notch called hilum through which ureter, blood vessels and nerves enter. Inner to the hilum is a broad funnel shaped space called the renal pelvis with projections called calyces. The outer layer of kidney is a tough capsule. Inside the kidney, there are two zones, an outer *cortex* and an inner *medulla*. The medulla is divided into a few conical masses (medullary pyramids) projecting into the calyces (sing.: calyx). The cortex extends in between the

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medullary pyramids as renal columns called **Columns of Bertini** (Figure 16.2).

Each kidney has nearly one million complex tubular structures called **nephrons** (Figure 16.3), which are the functional units. Each nephron has two parts – the glomerulus and the renal tubule. Glomerulus is a tuft of capillaries formed by the afferent arteriole – a fine branch of renal artery. Blood from the glomerulus is carried away by an efferent arteriole.

The renal tubule begins with a double walled cup-like structure called **Bowman's capsule**, which encloses the glomerulus. Glomerulus alongwith Bowman's capsule, is called the malpighian body or renal corpuscle (Figure 16.4). The tubule continues further to form a highly coiled network – **proximal convoluted tubule**

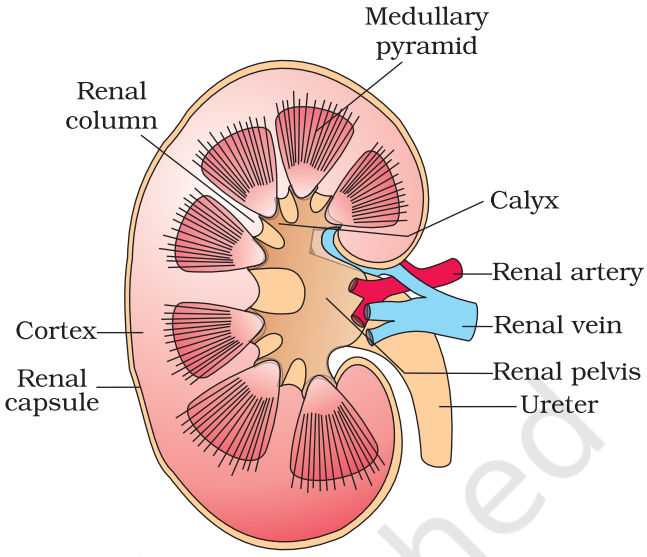

Figure 16.2 Longitudinal section (Diagrammatic) of Kidney

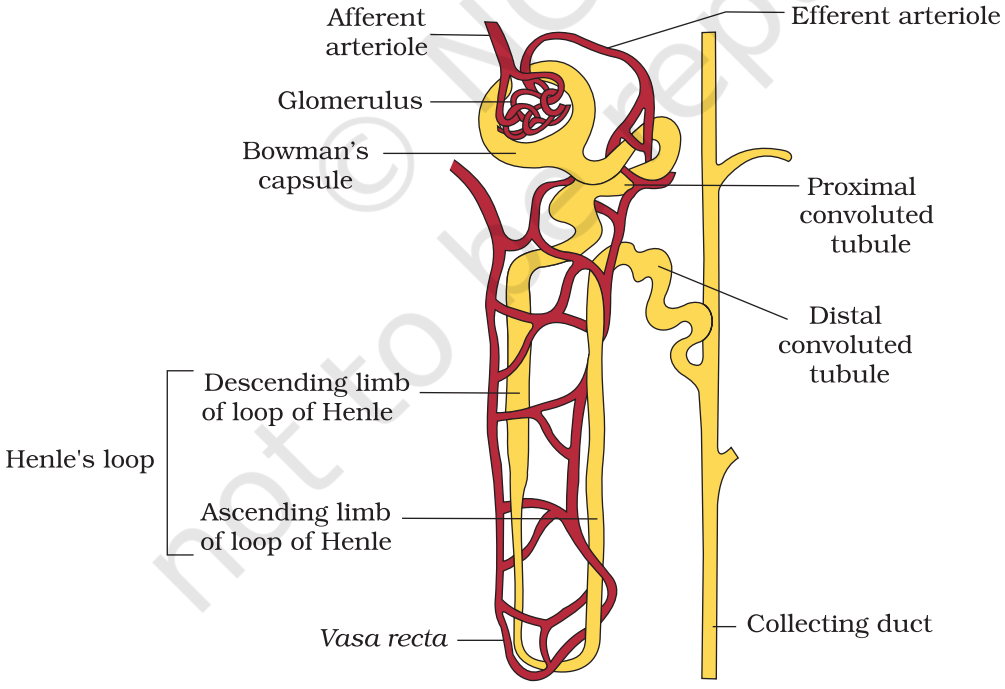

Figure 16.3 A diagrammatic representation of a nephron showing blood vessels, duct and tubule

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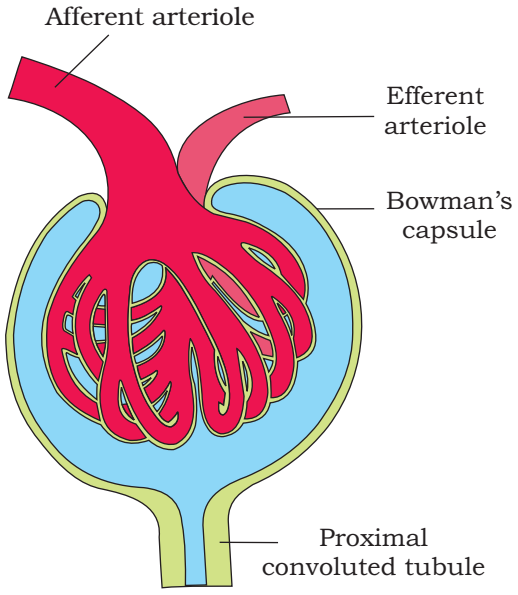

Figure 16.4 Malpighian body (renal corpuscle)

(PCT). A hairpin shaped **Henle's loop** is the next part of the tubule which has a descending and an ascending limb. The ascending limb continues as another highly coiled tubular region called **distal convoluted tubule** (DCT). The DCTs of many nephrons open into a straight tube called *collecting duct*, many of which converge and open into the renal pelvis through medullary pyramids in the calyces.

The Malpighian corpuscle, PCT and DCT of the nephron are situated in the cortical region of the kidney whereas the loop of Henle dips into the medulla. In majority of nephrons, the loop of Henle is too short and extends only very little into the medulla. Such nephrons are called cortical nephrons. In some of the nephrons, the loop of Henle is very long and runs deep into the medulla. These nephrons are called juxta medullary nephrons.

The efferent arteriole emerging from the glomerulus forms a fine capillary network around the renal tubule called the peritubular capillaries. A minute vessel of this network runs parallel to the Henle's loop forming a 'U' shaped *vasa recta*. *Vasa recta* is absent or highly reduced in cortical nephrons.

16.2 URINE FORMATION

Urine formation involves three main processes namely, glomerular filtration, reabsorption and secretion, that takes place in different parts of the nephron.

The first step in urine formation is the filtration of blood, which is carried out by the glomerulus and is called **glomerular filtration**. On an average, 1100-1200 ml of blood is filtered by the kidneys per minute which constitute roughly 1/5th of the blood pumped out by each ventricle of the heart in a minute. The glomerular capillary blood pressure causes filtration of blood through 3 layers, i.e., the endothelium of glomerular blood vessels, the epithelium of Bowman's capsule and a basement membrane between these two layers. The epithelial cells of Bowman's capsule called podocytes are arranged in an intricate manner so as to leave some minute spaces called filtration slits or slit pores. Blood is filtered so finely through these membranes, that almost all the constituents of the plasma except the proteins pass onto the lumen of the Bowman's capsule. Therefore, it is considered as a process of **ultra filtration.**

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The amount of the filtrate formed by the kidneys per minute is called **glomerular filtration rate** (GFR). GFR in a healthy individual is approximately 125 ml/minute, i.e., 180 litres per day !

The kidneys have built-in mechanisms for the regulation of glomerular filtration rate. One such efficient mechanism is carried out by juxta glomerular apparatus (JGA). JGA is a special sensitive region formed by cellular modifications in the distal convoluted tubule and the afferent arteriole at the location of their contact. A fall in GFR can activate the JG cells to release renin which can stimulate the glomerular blood flow and thereby the GFR back to normal.

A comparison of the volume of the filtrate formed per day (180 litres per day) with that of the urine released (1.5 litres), suggest that nearly 99 per cent of the filtrate has to be reabsorbed by the renal tubules. This process is called **reabsorption**. The tubular epithelial cells in different segments of nephron perform this either by active or passive mechanisms. For example, substances like glucose, amino acids, Na^+, etc., in the filtrate are reabsorbed actively whereas the nitrogenous wastes are absorbed by passive transport. Reabsorption of water also occurs passively in the initial segments of the nephron (Figure 16.5).

During urine formation, the tubular cells secrete substances like H^+, K^+ and ammonia into the filtrate. Tubular secretion is also an important step in urine formation as it helps in the maintenance of ionic and acid base balance of body fluids.

16.3 FUNCTION OF THE TUBULES

Proximal Convoluted Tubule (PCT): PCT is lined by simple cuboidal brush border epithelium which increases the surface area for reabsorption. Nearly all of the essential nutrients, and 70-80 per cent of electrolytes and water are reabsorbed by this segment. PCT also helps to maintain the pH and ionic balance of the body fluids by selective secretion of hydrogen ions and ammonia into the filtrate and by absorption of HCO_3^- from it.

Henle's Loop: Reabsorption is minimum in its ascending limb. However, this region plays a significant role in the maintenance of high osmolarity of medullary interstitial fluid. The descending limb of loop of Henle is permeable to water but almost impermeable to electrolytes. This concentrates the filtrate as it moves down. The ascending limb is impermeable to water but allows transport of electrolytes actively or passively. Therefore, as the concentrated filtrate pass upward, it gets diluted due to the passage of electrolytes to the medullary fluid.

Distal Convoluted Tubule (DCT): Conditional reabsorption of Na^+ and water takes place in this segment. DCT is also capable of reabsorption of HCO_3^- and selective secretion of hydrogen and potassium ions and NH_3 to maintain the pH and sodium-potassium balance in blood.

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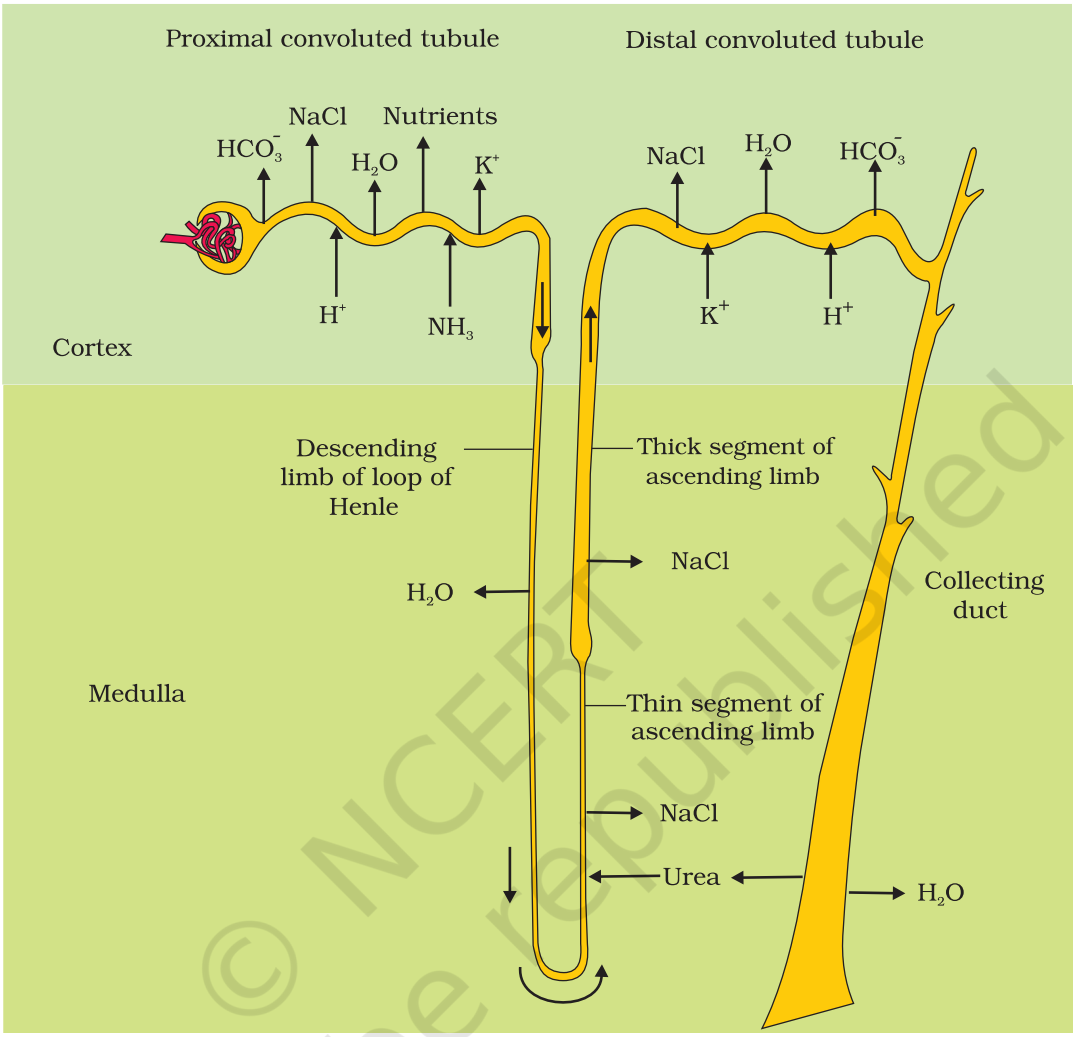

Figure 16.5 Reabsorption and secretion of major substances at different parts of the nephron (Arrows indicate direction of movement of materials.)

Collecting Duct: This long duct extends from the cortex of the kidney to the inner parts of the medulla. Large amounts of water could be reabsorbed from this region to produce a concentrated urine. This segment allows passage of small amounts of urea into the medullary interstitium to keep up the osmolarity. It also plays a role in the maintenance of pH and ionic balance of blood by the selective secretion of H^+ and K^+ ions (Figure 16.5).

16.4 Mechanism of Concentration of the Filtrate

Mammals have the ability to produce a concentrated urine. The Henle's loop and *vasa recta* play a significant role in this. The flow of filtrate in the two limbs of Henle's loop is in opposite directions and thus forms a counter current. The flow of blood through the two limbs of *vasa recta* is

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also in a counter current pattern. The proximity between the Henle's loop and *vasa recta*, as well as the counter current in them help in maintaining an increasing osmolarity towards the inner medullary interstitium, i.e., from 300 mOsmolL^{-1} in the cortex to about 1200 mOsmolL^{-1} in the inner medulla. This gradient is mainly caused by NaCl and urea. NaCl is transported by the ascending limb of Henle's loop which is exchanged with the descending limb of *vasa recta*. NaCl is returned to the interstitium by the ascending portion of *vasa recta*. Similarly, small amounts of urea enter the thin segment of the ascending limb of Henle's loop which is transported back to the interstitium by the collecting tubule. The above described transport of substances facilitated by the special arrangement of Henle's loop and *vasa recta* is called the **counter current mechanism** (Figure. 16.6). This mechanism helps to maintain a concentration gradient

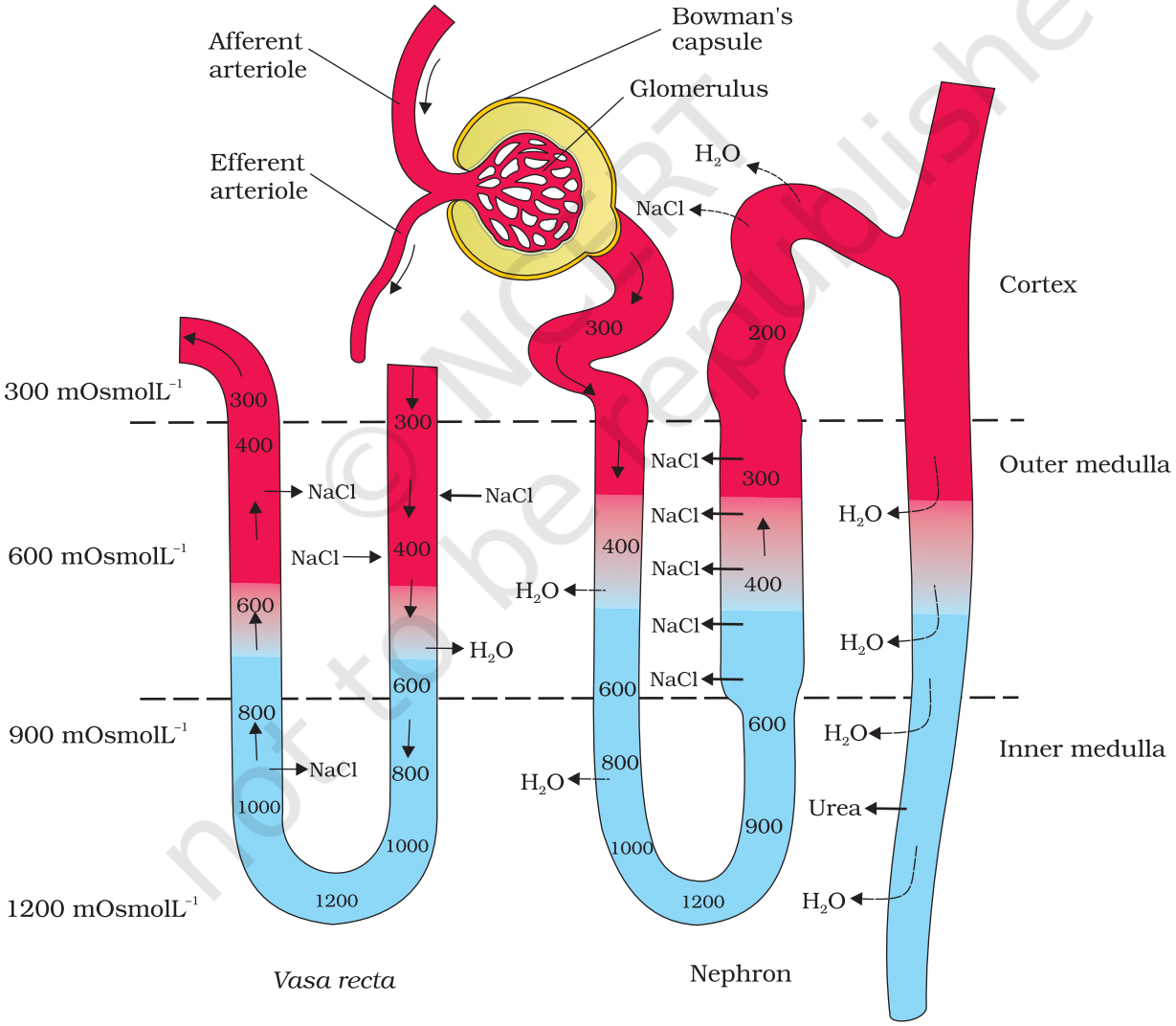

Figure 16.6 Diagrammatic representation of a nephron and *vasa recta* showing counter current mechanisms

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in the medullary interstitium. Presence of such interstitial gradient helps in an easy passage of water from the collecting tubule thereby concentrating the filtrate (urine). Human kidneys can produce urine nearly four times concentrated than the initial filtrate formed.

16.5 REGULATION OF KIDNEY FUNCTION

The functioning of the kidneys is efficiently monitored and regulated by hormonal feedback mechanisms involving the hypothalamus, JGA and to a certain extent, the heart.

Osmoreceptors in the body are activated by changes in blood volume, body fluid volume and ionic concentration. An excessive loss of fluid from the body can activate these receptors which stimulate the hypothalamus to release antidiuretic hormone (ADH) or vasopressin from the neurohypophysis. ADH facilitates water reabsorption from latter parts of the tubule, thereby preventing diuresis. An increase in body fluid volume can switch off the osmoreceptors and suppress the ADH release to complete the feedback. ADH can also affect the kidney function by its constrictory effects on blood vessels. This causes an increase in blood pressure. An increase in blood pressure can increase the glomerular blood flow and thereby the GFR.

The JGA plays a complex regulatory role. A fall in glomerular blood flow/glomerular blood pressure/GFR can activate the JG cells to release **renin** which converts angiotensinogen in blood to angiotensin I and further to angiotensin II. Angiotensin II, being a powerful vasoconstrictor, increases the glomerular blood pressure and thereby GFR. Angiotensin II also activates the adrenal cortex to release Aldosterone. Aldosterone causes reabsorption of Na^+ and water from the distal parts of the tubule. This also leads to an increase in blood pressure and GFR. This complex mechanism is generally known as the **Renin-Angiotensin** mechanism.

An increase in blood flow to the atria of the heart can cause the release of **Atrial Natriuretic Factor** (ANF). ANF can cause vasodilation (dilation of blood vessels) and thereby decrease the blood pressure. ANF mechanism, therefore, acts as a check on the renin-angiotensin mechanism.

16.6 MICTURITION

Urine formed by the nephrons is ultimately carried to the urinary bladder where it is stored till a voluntary signal is given by the central nervous system (CNS). This signal is initiated by the stretching of the urinary bladder as it gets filled with urine. In response, the stretch receptors on the walls of the bladder send signals to the CNS. The CNS passes on motor messages

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to initiate the contraction of smooth muscles of the bladder and simultaneous relaxation of the urethral sphincter causing the release of urine. The process of release of urine is called micturition and the neural mechanisms causing it is called the micturition reflex. An adult human excretes, on an average, 1 to 1.5 litres of urine per day. The urine formed is a light yellow coloured watery fluid which is slightly acidic (pH-6.0) and has a characterestic odour. On an average, 25-30 gm of urea is excreted out per day. Various conditions can affect the characteristics of urine. Analysis of urine helps in clinical diagnosis of many metabolic discorders as well as malfunctioning of the kidney. For example, presence of glucose (Glycosuria) and ketone bodies (Ketonuria) in urine are indicative of diabetes mellitus.

16.7 ROLE OF OTHER ORGANS IN EXCRETION

Other than the kidneys, lungs, liver and skin also help in the elimination of excretory wastes.

Our lungs remove large amounts of CO_2 (approximately 200mL/ minute) and also significant quantities of water every day. Liver, the largest gland in our body, secretes bile-containing substances like bilirubin, biliverdin, cholesterol, degraded steroid hormones, vitamins and drugs. Most of these substances ultimately pass out along with digestive wastes.

The sweat and sebaceous glands in the skin can eliminate certain substances through their secretions. Sweat produced by the sweat glands is a watery fluid containing NaCl, small amounts of urea, lactic acid, etc. Though the primary function of sweat is to facilitate a cooling effect on the body surface, it also helps in the removal of some of the wastes mentioned above. Sebaceous glands eliminate certain substances like sterols, hydrocarbons and waxes through sebum. This secretion provides a protective oily covering for the skin. Do you know that small amounts of nitrogenous wastes could be eliminated through saliva too?

16.8 DISORDERS OF THE EXCRETORY SYSTEM

Malfunctioning of kidneys can lead to accumulation of urea in blood, a condition called **uremia**, which is highly harmful and may lead to kidney failure. In such patients, urea can be removed by a process called **hemodialysis**. During the process of haemodialysis, the blood drained from a convenient artery is pumped into a dialysing unit called **artificial kidney**. Blood drained from a convenient artery is pumped into a dialysing unit after adding an anticoagulant like heparin. The unit contains a coiled cellophane tube surrounded by a fluid (dialysing fluid) having the same

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composition as that of plasma except the nitrogenous wastes. The porous cellophane membrance of the tube allows the passage of molecules based on concentration gradient. As nitrogenous wastes are absent in the dialysing fluid, these substances freely move out, thereby clearing the blood. The cleared blood is pumped back to the body through a vein after adding anti-heparin to it. This method is a boon for thousands of uremic patients all over the world.

Kidney transplantation is the ultimate method in the correction of acute **renal failures** (kidney failure). A functioning kidney is used in transplantation from a donor, preferably a close relative, to minimise its chances of rejection by the immune system of the host. Modern clinical procedures have increased the success rate of such a complicated technique.

Renal calculi: Stone or insoluble mass of crystallised salts (oxalates, etc.) formed within the kidney.

Glomerulonephritis: Inflammation of glomeruli of kidney.

SUMMARY

Many nitrogen containing substances, ions, CO_2, water, etc., that accumulate in the body have to be eliminated. Nature of nitrogenous wastes formed and their excretion vary among animals, mainly depending on the habitat (availability of water). Ammonia, urea and uric acid are the major nitrogenous wastes excreted.

Protonephridia, nephridia, malpighian tubules, green glands and the kidneys are the common excretory organs in animals. They not only eliminate nitrogenous wastes but also help in the maintenance of ionic and acid-base balance of body fluids.

In humans, the excretory system consists of one pair of kidneys, a pair of ureters, a urinary bladder and a urethra. Each kidney has over a million tubular structures called nephrons. Nephron is the functional unit of kidney and has two portions – glomerulus and renal tubule. Glomerulus is a tuft of capillaries formed from afferent arterioles, fine branches of renal artery. The renal tubule starts with a double walled Bowman's capsule and is further differentiated into a proximal convoluted tubule (PCT), Henle's loop (HL) and distal convoluted tubule (DCT). The DCTs of many nephrons join to a common collecting duct many of which ultimately open into the renal pelvis through the medullary pyramids. The Bowman's capsule encloses the glomerulus to form Malpighian or renal corpuscle.

Urine formation involves three main processes, i.e., filtration, reabsorption and secretion. Filtration is a non-selective process performed by the glomerulus using the glomerular capillary blood pressure. About 1200 ml of blood is filtered by the glomerulus per minute to form 125 ml of filtrate in the Bowman's capsule per

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minute (GFR). JGA, a specialised portion of the nephrons, plays a significant role in the regulation of GFR. Nearly 99 per cent reabsorption of the filtrate takes place through different parts of the nephrons. PCT is the major site of reabsorption and selective secretion. HL primarily helps to maintain osmolar gradient (300 mOsmolL^{-1} -1200 mOsmolL^{-1}) within the kidney interstitium. DCT and collecting duct allow extensive reabsorption of water and certain electrolytes, which help in osmoregulation: H^+, K^+ and NH_3 could be secreted into the filtrate by the tubules to maintain the ionic balance and pH of body fluids.

A counter current mechanism operates between the two limbs of the loop of Henle and those of *vasa recta* (capillary parallel to Henle's loop). The filtrate gets concentrated as it moves down the descending limb but is diluted by the ascending limb. Electrolytes and urea are retained in the interstitium by this arrangement. DCT and collecting duct concentrate the filtrate about four times, i.e., from 300 mOsmolL^{-1} to 1200 mOsmolL^{-1}, an excellent mechanism of conservation of water. Urine is stored in the urinary bladder till a voluntary signal from CNS carries out its release through urethra, i.e., micturition. Skin, lungs and liver also assist in excretion.

EXERCISES

1. Define Glomerular Filtration Rate (GFR)
2. Explain the autoregulatory mechanism of GFR.
3. Indicate whether the following statements are true or false :
   (a) Micturition is carried out by a reflex.
   (b) ADH helps in water elimination, making the urine hypotonic.
   (c) Protein-free fluid is filtered from blood plasma into the Bowman's capsule.
   (d) Henle's loop plays an important role in concentrating the urine.
   (e) Glucose is actively reabsorbed in the proximal convoluted tubule.
4. Give a brief account of the counter current mechanism.
5. Describe the role of liver, lungs and skin in excretion.
6. Explain micturition.
7. Match the items of column I with those of column II :

Column I	**Column II**
(a) Ammonotelism	(i) Birds
(b) Bowman's capsule	(ii) Water reabsorption
(c) Micturition	(iii) Bony fish
(d) Uricotelism	(iv) Urinary bladder
(d) ADH	(v) Renal tubule

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8. What is meant by the term osmoregulation?
9. Terrestrial animals are generally either ureotelic or uricotelic, not ammonotelic, why ?
10. What is the significance of juxta glomerular apparatus (JGA) in kidney function?
11. Name the following:
    (a) A chordate animal having flame cells as excretory structures
    (b) Cortical portions projecting between the medullary pyramids in the human kidney
    (c) A loop of capillary running parallel to the Henle's loop.
12. Fill in the gaps :
    (a) Ascending limb of Henle's loop is _____ to water whereas the descending limb is _____ to it.
    (b) Reabsorption of water from distal parts of the tubules is facilitated by hormone _____.
    (c) Dialysis fluid contain all the constituents as in plasma except _____.
    (d) A healthy adult human excretes (on an average) _____ gm of urea/day.

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Chapter 17
Locomotion and Movement

17.1 *Types of Movement*

17.2 *Muscle*

17.3 *Skeletal System*

17.4 *Joints*

17.5 *Disorders of Muscular and Skeletal System*

Movement is one of the significant features of living beings. Animals and plants exhibit a wide range of movements. Streaming of protoplasm in the unicellular organisms like *Amoeba* is a simple form of movement. Movement of cilia, flagella and tentacles are shown by many organisms. Human beings can move limbs, jaws, eyelids, tongue, etc. Some of the movements result in a change of place or location. Such voluntary movements are called **locomotion**. Walking, running, climbing, flying and swimming are all some forms of locomotory movements. Locomotory structures need not be different from those affecting other types of movements. For example, in *Paramoecium*, cilia helps in the movement of food through cytopharynx and in locomotion as well. *Hydra* can use its tentacles for capturing its prey and also use them for locomotion. We use limbs for changes in body postures and locomotion as well. The above observations suggest that movements and locomotion cannot be studied separately. The two may be linked by stating that all locomotions are movements but all movements are not locomotions.

Methods of locomotion performed by animals vary with their habitats and the demand of the situation. However, locomotion is generally for search of food, shelter, mate, suitable breeding grounds, favourable climatic conditions or to escape from enemies/predators.

17.1 Types of Movement

Cells of the human body exhibit three main types of movements, namely, amoeboid, ciliary and muscular.

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Some specialised cells in our body like macrophages and leucocytes in blood exhibit amoeboid movement. It is effected by pseudopodia formed by the streaming of protoplasm (as in *Amoeba*). Cytoskeletal elements like microfilaments are also involved in amoeboid movement.

Ciliary movement occurs in most of our internal tubular organs which are lined by ciliated epithelium. The coordinated movements of cilia in the trachea help us in removing dust particles and some of the foreign substances inhaled along with the atmospheric air. Passage of ova through the female reproductive tract is also facilitated by the ciliary movement.

Movement of our limbs, jaws, tongue, etc, require muscular movement. The contractile property of muscles are effectively used for locomotion and other movements by human beings and majority of multicellular organisms. Locomotion requires a perfect coordinated activity of muscular, skeletal and neural systems. In this chapter, you will learn about the types of muscles, their structure, mechanism of their contraction and important aspects of the skeletal system.

17.2 MUSCLE

You have studied in Chapter 8 that the cilia and flagella are the outgrowths of the cell membrane. **Flagellar movement** helps in the swimming of spermatozoa, maintenance of water current in the canal system of sponges and in locomotion of Protists like *Euglena.* Muscle is a specialised tissue of mesodermal origin. About 40-50 per cent of the body weight of a human adult is contributed by muscles. They have special properties like excitability, contractility, extensibility and elasticity. Muscles have been classified using different criteria, namely location, appearance and nature of regulation of their activities. Based on their location, three types of muscles are identified : (i) Skeletal (ii) Visceral and (iii) Cardiac.

Skeletal muscles are closely associated with the skeletal components of the body. They have a striped appearance under the microscope and hence are called **striated muscles**. As their activities are under the voluntary control of the nervous system, they are known as voluntary muscles too. They are primarily involved in locomotory actions and changes of body postures.

Visceral muscles are located in the inner walls of hollow visceral organs of the body like the alimentary canal, reproductive tract, etc. They do not exhibit any striation and are smooth in appearance. Hence, they are called **smooth muscles (nonstriated muscle)**. Their activities are not under the voluntary control of the nervous system and are therefore known as involuntary muscles. They assist, for example, in the transportation of food through the digestive tract and gametes through the genital tract.

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As the name suggests, **Cardiac muscles** are the muscles of heart. Many cardiac muscle cells assemble in a branching pattern to form a cardiac muscle. Based on appearance, cardiac muscles are striated. They are involuntary in nature as the nervous system does not control their activities directly.

Let us examine a skeletal muscle in detail to understand the structure and mechanism of contraction. Each organised skeletal muscle in our body is made of a number of **muscle bundles** or **fascicles** held together by a common collagenous connective tissue layer called **fascia**. Each muscle bundle contains a number of muscle fibres (Figure 17.1). Each

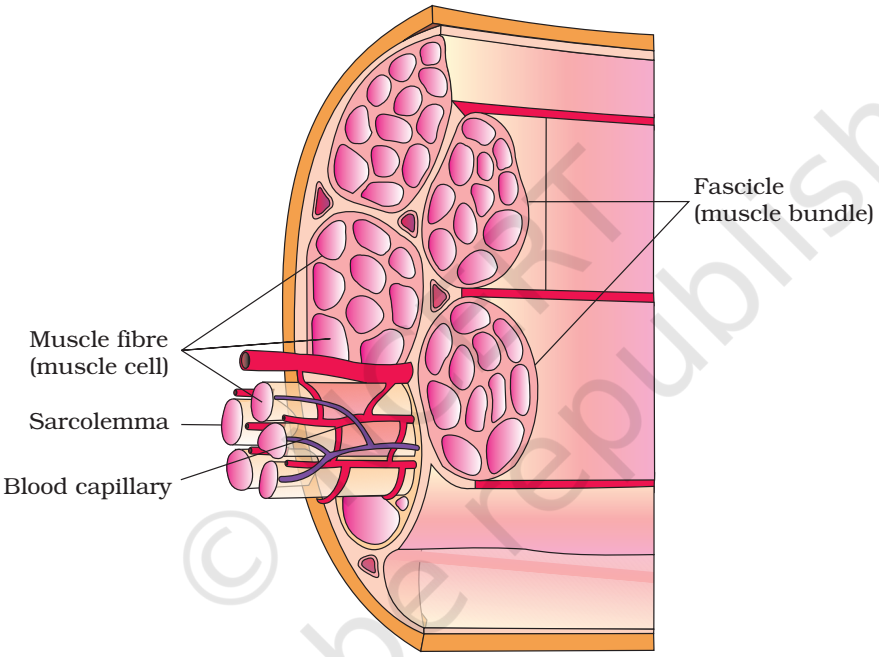

Figure 17.1 Diagrammatic cross sectional view of a muscle showing muscle bundles and muscle fibres

muscle fibre is lined by the plasma membrane called sarcolemma enclosing the sarcoplasm. Muscle fibre is a syncitium as the sarcoplasm contains many nuclei. The endoplasmic reticulum, i.e., sarcoplasmic reticulum of the muscle fibres is the store house of calcium ions. A characteristic feature of the muscle fibre is the presence of a large number of parallelly arranged filaments in the sarcoplasm called myofilaments or **myofibrils**. Each myofibril has alternate dark and light bands on it. A detailed study of the myofibril has established that the striated appearance is due to the distribution pattern of two important proteins – **Actin** and **Myosin**. The light bands contain actin and is called I-band or Isotropic band, whereas the dark band called 'A' or Anisotropic band contains

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myosin. Both the proteins are arranged as rod-like structures, parallel to each other and also to the longitudinal axis of the myofibrils. Actin filaments are thinner as compared to the myosin filaments, hence are commonly called thin and thick filaments respectively. In the centre of each 'I' band is an elastic fibre called 'Z' line which bisects it. The thin filaments are firmly attached to the 'Z' line. The thick filaments in the 'A' band are also held together in the middle of this band by a thin fibrous membrane called 'M' line. The 'A' and 'I' bands are arranged alternately throughout the length of the myofibrils. The portion of the myofibril between two successive 'Z' lines is considered as the functional unit of contraction and is called a sarcomere (Figure 17.2). In a resting state, the edges of thin filaments on either side of the thick filaments partially overlap the free ends of the thick filaments leaving the central part of the thick filaments. This central part of thick filament, not overlapped by thin filaments is called the 'H' zone.

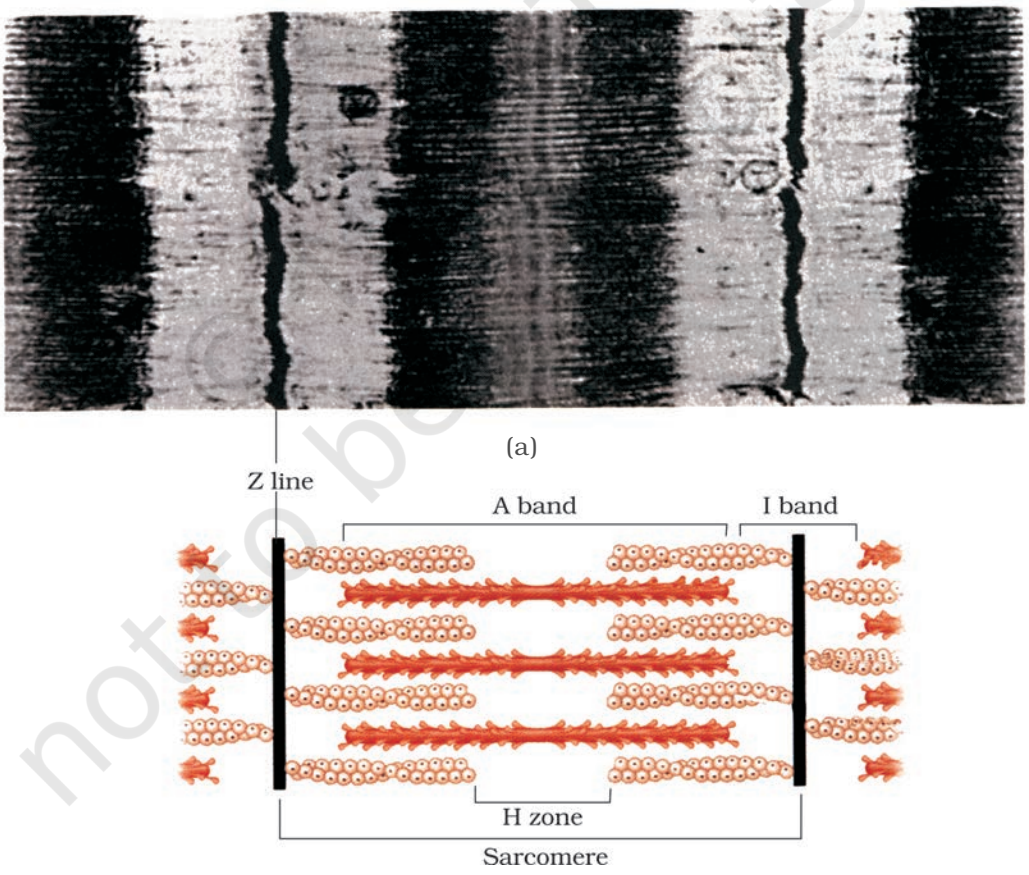

Figure 17.2 Diagrammatic representation of (a) anatomy of a muscle fibre showing a sarcomere (b) a sarcomere

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17.2.1 Structure of Contractile Proteins

Each actin (thin) filament is made of two 'F' (filamentous) actins helically wound to each other. Each 'F' actin is a polymer of monomeric 'G' (Globular) actins. Two filaments of another protein, tropomyosin also run close to the 'F' actins throughout its length. A complex protein Troponin is distributed at regular intervals on the tropomyosin. In the resting state a subunit of troponin masks the active binding sites for myosin on the actin filaments (Figure 17.3a).

Each myosin (thick) filament is also a polymerised protein. Many monomeric proteins called Meromyosins (Figure 17.3b) constitute one thick filament. Each meromyosin has two important parts, a globular head with a short arm and a tail, the former being called the heavy meromyosin (HMM) and the latter, the light meromyosin (LMM). The HMM component, i.e.; the head and short arm projects outwards at regular distance and angle from each other from the surface of a polymerised myosin filament and is known as cross arm. The globular head is an active ATPase enzyme and has binding sites for ATP and active sites for actin.

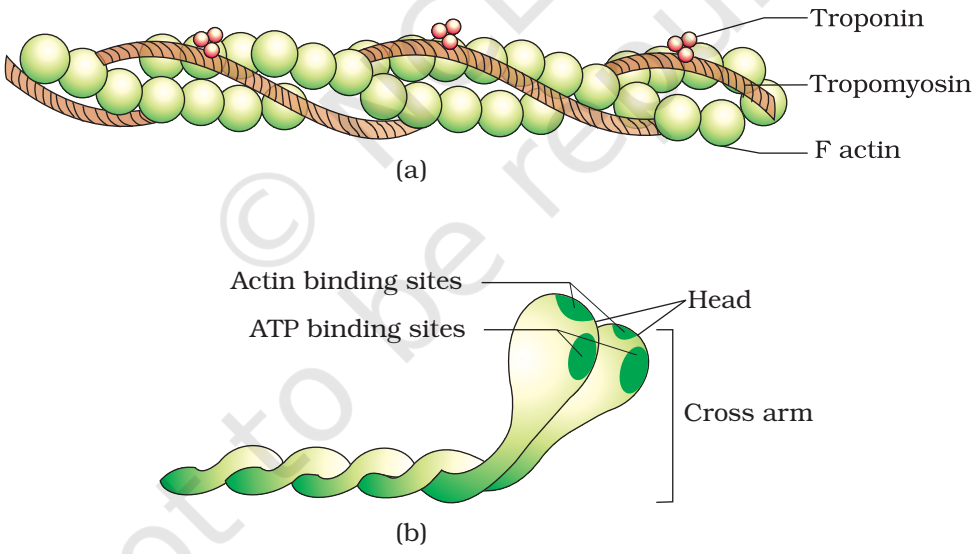

Figure 17.3 (a) An actin (thin) filament (b) Myosin monomer (Meromyosin)

17.2.2 Mechanism of Muscle Contraction

Mechanism of muscle contraction is best explained by the sliding filament theory which states that contraction of a muscle fibre takes place by the sliding of the thin filaments over the thick filaments.

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Muscle contraction is initiated by a signal sent by the central nervous system (CNS) via a motor neuron. A motor neuron along with the muscle fibres connected to it constitute a motor unit. The junction between a motor neuron and the sarcolemma of the muscle fibre is called the neuromuscular junction or motor-end plate. A neural signal reaching this junction releases a neurotransmitter (Acetyl choline) which generates an action potential in the sarcolemma. This spreads through the muscle fibre and causes the release of calcium ions into the sarcoplasm. Increase in Ca^{++} level leads to the binding of calcium with a subunit of troponin on actin filaments and thereby remove the masking of active sites for myosin. Utilising the energy from ATP hydrolysis, the myosin head now binds to the exposed active sites on actin to form a cross bridge (Figure 17.4).

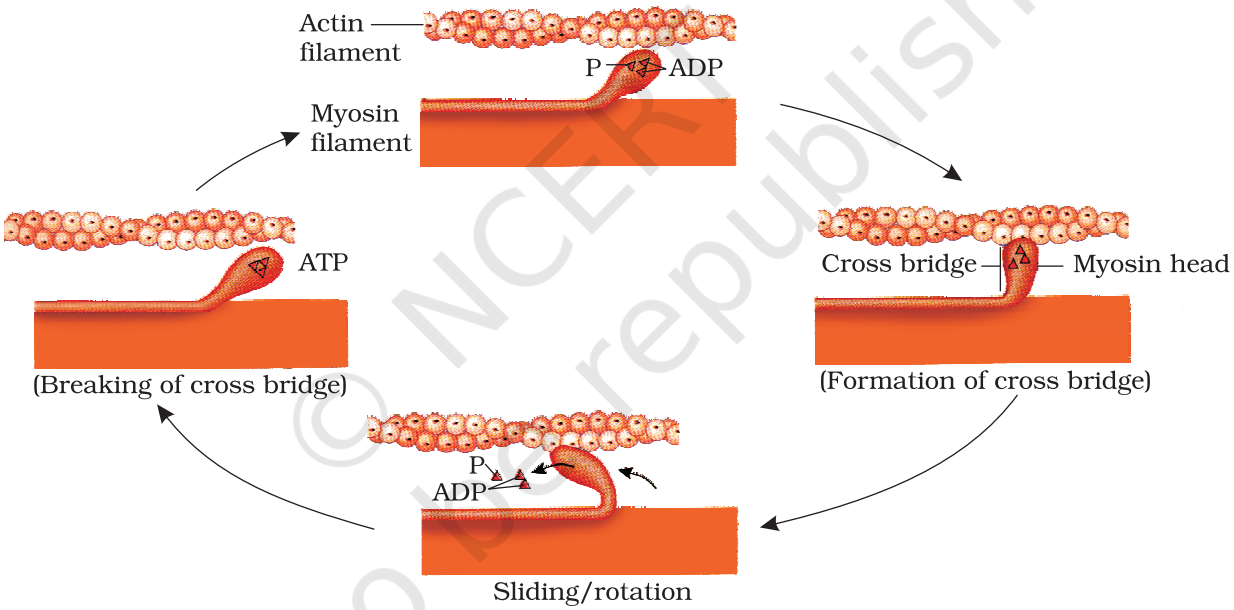

Figure 17.4 Stages in cross bridge formation, rotation of head and breaking of cross bridge

This pulls the attached actin filaments towards the centre of 'A' band. The 'Z' line attached to these actins are also pulled inwards thereby causing a shortening of the sarcomere, i.e., contraction. It is clear from the above steps, that during shortening of the muscle, i.e., contraction, the 'I' bands get reduced, whereas the 'A' bands retain the length (Figure 17.5). The myosin, releasing the ADP and P_i goes back to its relaxed state. A new ATP binds and the cross-bridge is broken (Figure 17.4). The ATP is again hydrolysed by the myosin head and the cycle of cross bridge formation

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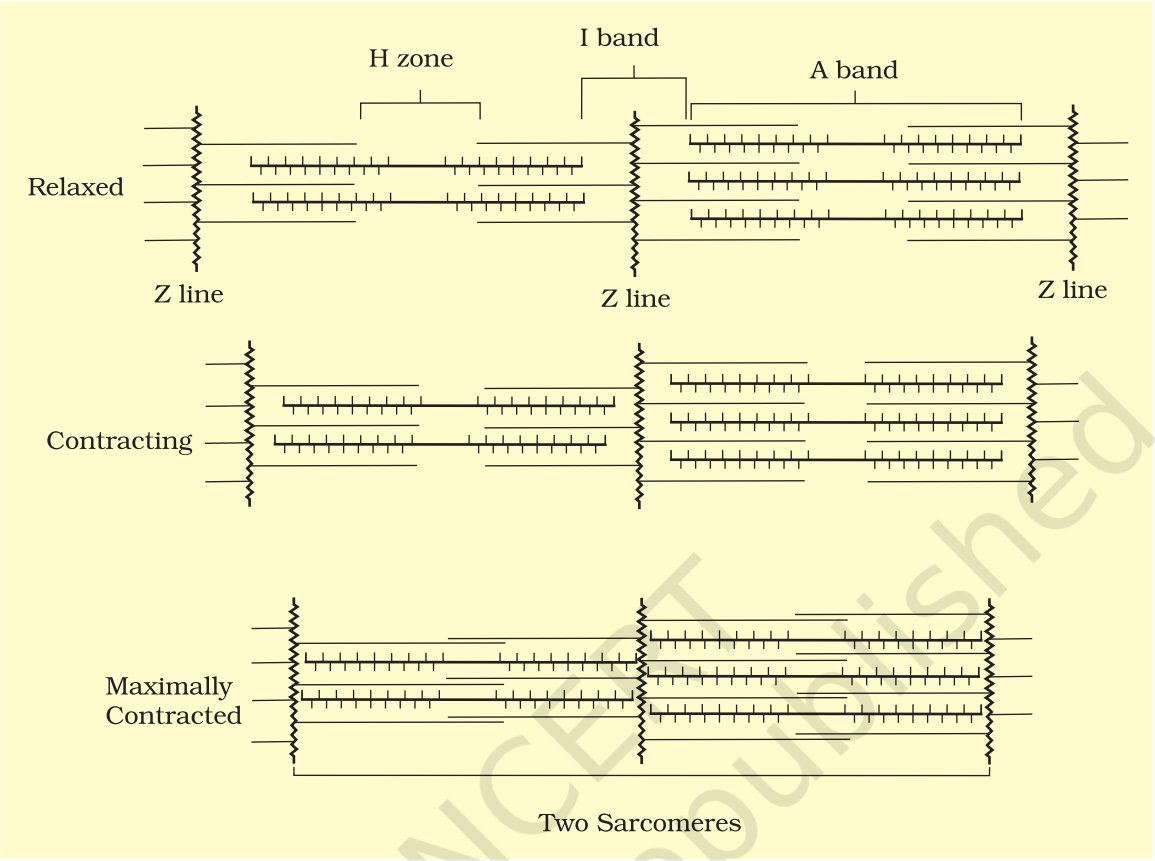

Figure 17.5 Sliding-filament theory of muscle contraction (movement of the thin filaments and the relative size of the I band and H zones)

and breakage is repeated causing further sliding. The process continues till the Ca^{++} ions are pumped back to the sarcoplasmic cisternae resulting in the masking of actin filaments. This causes the return of 'Z' lines back to their original position, i.e., relaxation. The reaction time of the fibres can vary in different muscles. Repeated activation of the muscles can lead to the accumulation of lactic acid due to anaerobic breakdown of glycogen in them, causing fatigue. Muscle contains a red coloured oxygen storing pigment called myoglobin. Myoglobin content is high in some of the muscles which gives a reddish appearance. Such muscles are called the Red fibres. These muscles also contain plenty of mitochondria which can utilise the large amount of oxygen stored in them for ATP production. These muscles, therefore, can also be called aerobic muscles. On the other hand, some of the muscles possess very less quantity of myoglobin and therefore, appear pale or whitish. These are the White fibres. Number of mitochondria are also few in them, but the amount of sarcoplasmic reticulum is high. They depend on anaerobic process for energy.

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17.3 SKELETAL SYSTEM

Skeletal system consists of a framework of bones and a few cartilages. This system has a significant role in movement shown by the body. Imagine chewing food without jaw bones and walking around without the limb bones. Bone and cartilage are specialised connective tissues. The former has a very hard matrix due to calcium salts in it and the latter has slightly pliable matrix due to chondroitin salts. In human beings, this system is made up of 206 bones and a few cartilages. It is grouped into two principal divisions – the axial and the appendicular skeleton.

Axial skeleton *comprises 80 bones distributed along the main axis of the body. The skull, vertebral column, sternum and ribs constitute axial skeleton. The* **skull** *(Figure 17.6) is composed of two*

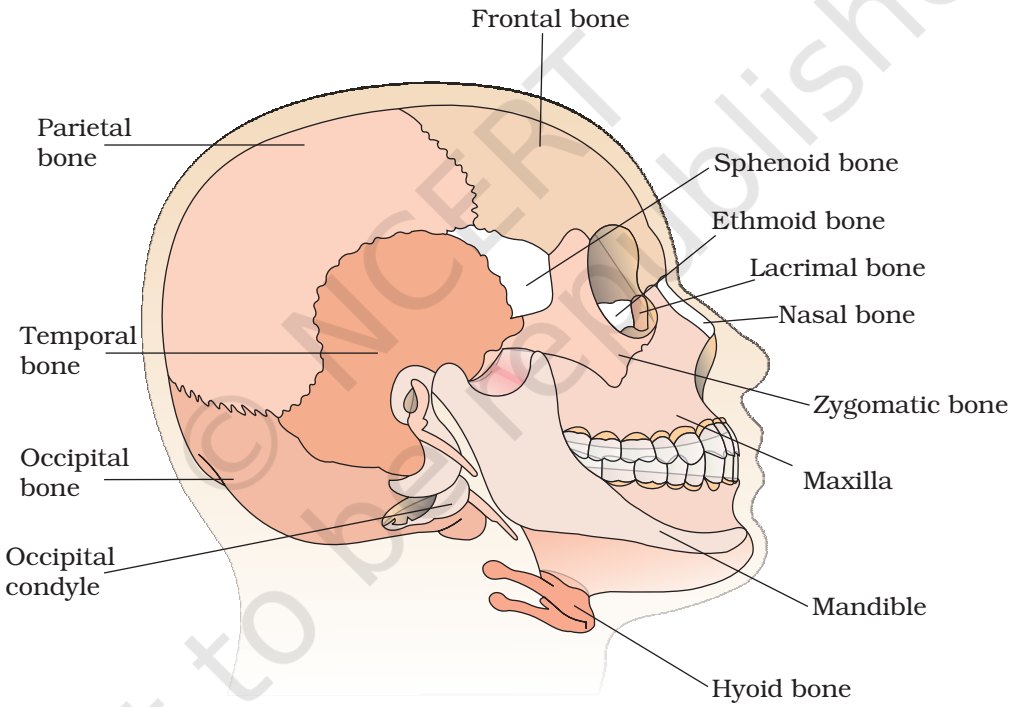

Figure 17.6 *Diagrammatic view of human skull*

sets of bones – cranial and facial, that totals to 22 bones. Cranial bones are 8 in number. They form the hard protective outer covering, cranium for the brain. The facial region is made up of 14 skeletal elements which form the front part of the skull. A single U-shaped bone called hyoid is present at the base of the buccal cavity. Each middle ear contains three tiny bones – Malleus, Incus and Stapes, collectively called **Ear Ossicles**. *The skull region articulates with the superior region of the*

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vertebral column with the help of two occipital condyles (dicondylic skull).

Our **vertebral column** (Figure 17.7) is formed by 26 serially arranged units called vertebrae and is dorsally placed. It extends from the base of the skull and constitutes the main framework of the trunk. Each vertebra has a central hollow portion (neural canal) through which the spinal cord passes. First vertebra is the atlas and it articulates with the occipital condyles. The vertebral column is differentiated into cervical (7), thoracic (12), lumbar (5), sacral (1-fused) and coccygeal (1-fused) regions starting from the skull. The number of cervical vertebrae are seven in almost all mammals including human beings. The vertebral column protects the spinal cord, supports the head and serves as the point of attachment for the ribs and musculature of the back. **Sternum** is a flat bone on the ventral midline of thorax.

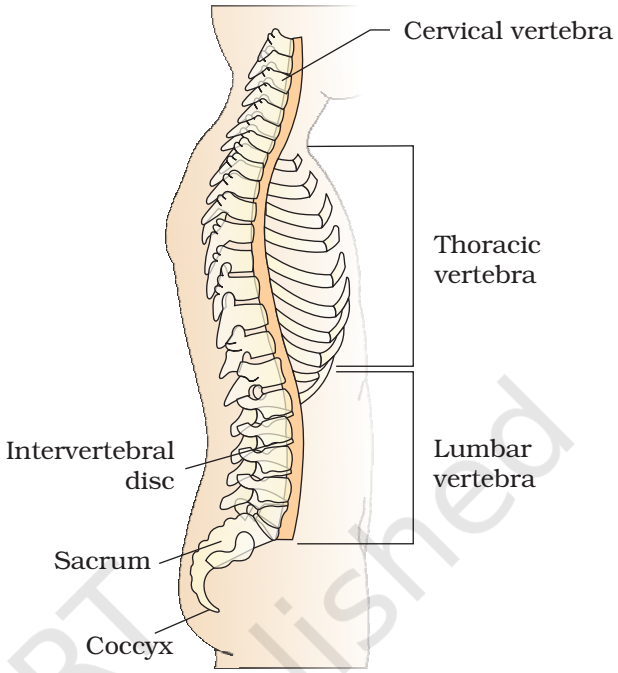

Figure 17.7 Vertebral column (right lateral view)

There are 12 pairs of **ribs.** Each rib is a thin flat bone connected dorsally to the vertebral column and ventrally to the sternum. It has two articulation surfaces on its dorsal end and is hence called bicephalic. First seven pairs of ribs are called true ribs. Dorsally, they are attached to the thoracic vertebrae and ventrally connected to the sternum with the help of hyaline cartilage. The 8th, 9th and 10th pairs of ribs do not articulate directly with the sternum but join the seventh rib with the help of hyaline cartilage. These are called vertebrochondral (false) ribs. Last 2 pairs (11th and 12th) of ribs are not connected ventrally and are therefore, called floating ribs. Thoracic vertebrae, ribs and sternum together form the rib cage (Figure 17.8).

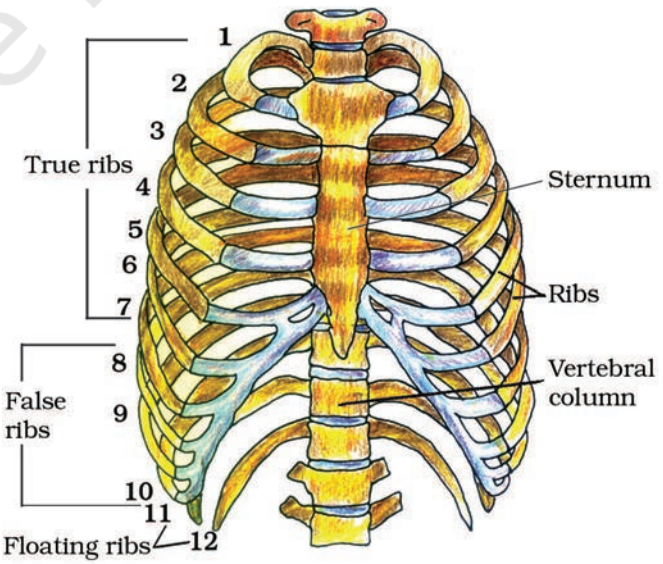

Figure 17.8 Ribs and rib cage

The bones of the limbs along with their girdles constitute the **appendicular skeleton.** Each **limb** is made of 30 bones. The bones of the hand (fore limb) are

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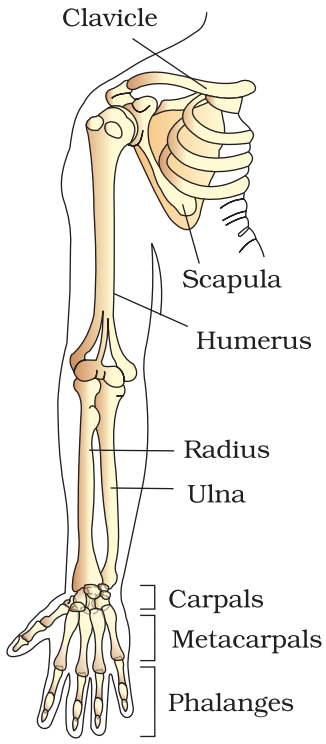

Figure 17.9 Right pectoral girdle and upper arm. (frontal view)

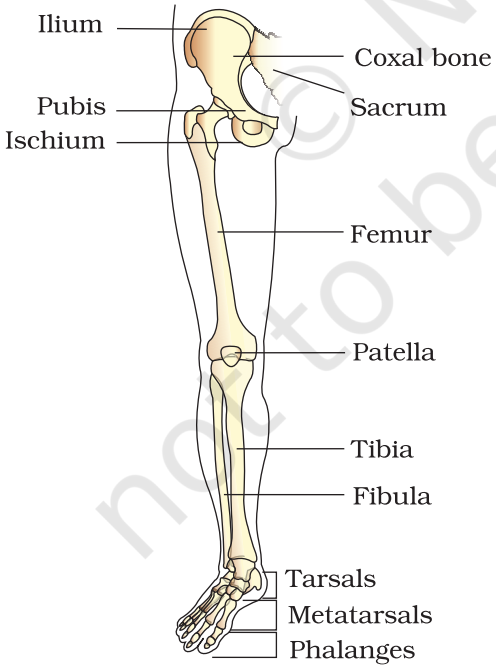

Figure 17.10 Right pelvic girdle and lower limb bones (frontal view)

humerus, radius and ulna, carpals (wrist bones – 8 in number), metacarpals (palm bones – 5 in number) and phalanges (digits – 14 in number) (Figure 17.9). Femur (thigh bone – the longest bone), tibia and fibula, tarsals (ankle bones – 7 in number), metatarsals (5 in number) and phalanges (digits – 14 in number) are the bones of the legs (hind limb) (Figure 17.10). A cup shaped bone called patella cover the knee ventrally (knee cap).

Pectoral and **Pelvic girdle** bones help in the articulation of the upper and the lower limbs respectively with the axial skeleton. Each girdle is formed of two halves. Each half of pectoral girdle consists of a clavicle and a scapula (Figure 17.9). Scapula is a large triangular flat bone situated in the dorsal part of the thorax between the second and the seventh ribs. The dorsal, flat, triangular body of scapula has a slightly elevated ridge called the spine which projects as a flat, expanded process called the acromion. The clavicle articulates with this. Below the acromion is a depression called the glenoid cavity which articulates with the head of the humerus to form the shoulder joint. Each clavicle is a long slender bone with two curvatures. This bone is commonly called the collar bone.

Pelvic girdle consists of two coxal bones (Figure 17.10). Each coxal bone is formed by the fusion of three bones – ilium, ischium and pubis. At the point of fusion of the above bones is a cavity called acetabulum to which the thigh bone articulates. The two halves of the pelvic girdle meet ventrally to form the pubic symphysis containing fibrous cartilage.

17.4 JOINTS

Joints are essential for all types of movements involving the bony parts of the body. Locomotory movements are no exception to

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this. Joints are points of contact between bones, or between bones and cartilages. Force generated by the muscles is used to carry out movement through joints, where the joint acts as a fulcrum. The movability at these joints vary depending on different factors. Joints have been classified into three major structural forms, namely, fibrous, cartilaginous and synovial.

Fibrous joints do not allow any movement. This type of joint is shown by the flat skull bones which fuse end-to-end with the help of dense fibrous connective tissues in the form of sutures, to form the cranium.

In **cartilaginous joints,** the bones involved are joined together with the help of cartilages. The joint between the adjacent vertebrae in the vertebral column is of this pattern and it permits limited movements.

Synovial joints are characterised by the presence of a fluid filled synovial cavity between the articulating surfaces of the two bones. Such an arragement allows considerable movement. These joints help in locomotion and many other movements. Ball and socket joint (between humerus and pectoral girdle), hinge joint (knee joint), pivot joint (between atlas and axis), gliding joint (between the carpals) and saddle joint (between carpal and metacarpal of thumb) are some examples.

17.5 DISORDERS OF MUSCULAR AND SKELETAL SYSTEM

Myasthenia gravis: Auto immune disorder affecting neuromuscular junction leading to fatigue, weakening and paralysis of skeletal muscle.

Muscular dystrophy: Progressive degeneration of skeletal muscle mostly due to genetic disorder.

Tetany: Rapid spasms (wild contractions) in muscle due to low Ca^{++} in body fluid.

Arthritis: Inflammation of joints.

Osteoporosis: Age-related disorder characterised by decreased bone mass and increased chances of fractures. Decreased levels of estrogen is a common cause.

Gout: Inflammation of joints due to accumulation of uric acid crystals.

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SUMMARY

Movement is an essential feature of all living beings. Protoplasmic streaming, ciliary movements, movements of fins, limbs, wings, etc., are some forms exhibited by animals. A voluntary movement which causes the animal to change its place, is

called locomotion. Animals move generally in search of food, shelter, mate, breeding ground, better climate or to protect themselves.

The cells of the human body exhibit amoeboid, ciliary and muscular movements. Locomotion and many other movements require coordinated muscular activities. Three types of muscles are present in our body. Skeletal muscles are attached to skeletal elements. They appear striated and are voluntary in nature. Visceral muscles, present in the inner walls of visceral organs are nonstriated and involuntary. Cardiac muscles are the muscles of the heart. They are striated, branched and involuntary. Muscles possess excitability, contractility, extensibility and elasticity.

Muscle fibre is the anatomical unit of muscle. Each muscle fibre has many parallelly arranged myofibrils. Each myofibril contains many serially arranged units called sarcomere which are the functional units. Each sarcomere has a central 'A' band made of thick myosin filaments, and two half 'I' bands made of thin actin filaments on either side of it marked by 'Z' lines. Actin and myosin are polymerised proteins with contractility. The active sites for myosin on resting actin filament are masked by a protein-troponin. Myosin head contains ATPase and has ATP binding sites and active sites for actin. A motor neuron carries signal to the muscle fibre which generates an action potential in it. This causes the release of Ca^{++} from sarcoplasmic reticulum. Ca^{++} activates actin which binds to the myosin head to form a cross bridge. These cross bridges pull the actin filaments causing them to slide over the myosin filaments and thereby causing contraction. Ca^{++} are then returned to sarcoplasmic reticulum which inactivate the actin. Cross bridges are broken and the muscles relax.

Repeated stimulation of muscles leads to fatigue. Muscles are classified as Red and White fibres based primarily on the amount of red coloured myoglobin pigment in them.

Bones and cartilages constitute our skeletal system. The skeletal system is divisible into axial and appendicular. Skull, vertebral column, ribs and sternum constitute the axial skeleton. Limb bones and girdles form the appendicular skeleton. Three types of joints are formed between bones or between bone and cartilage – fibrous, cartilaginous and synovial. Synovial joints allow considerable movements and therefore, play a significant role in locomotion.

EXERCISES

1. Draw the diagram of a sarcomere of skeletal muscle showing different regions.
2. Define sliding filament theory of muscle contraction.
3. Describe the important steps in muscle contraction.

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4. Write true or false. If false change the statement so that it is true.
   (a) Actin is present in thin filament
   (b) H-zone of striated muscle fibre represents both thick and thin filaments.
   (c) Human skeleton has 206 bones.
   (d) There are 11 pairs of ribs in man.
   (e) Sternum is present on the ventral side of the body.
5. Write the difference between :
   (a) Actin and Myosin
   (b) Red and White muscles
   (c) Pectoral and Pelvic girdle
6. Match Column I with Column II :

Column I	**Column II**
(a) Smooth muscle	(i) Myoglobin
(b) Tropomyosin	(ii) Thin filament
(c) Red muscle	(iii) Sutures
(d) Skull	(iv) Involuntary

7. What are the different types of movements exhibited by the cells of human body?
8. How do you distinguish between a skeletal muscle and a cardiac muscle?
9. Name the type of joint between the following:-
   (a) atlas/axis
   (b) carpal/metacarpal of thumb
   (c) between phalanges
   (d) femur/acetabulum
   (e) between cranial bones
   (f) between pubic bones in the pelvic girdle
10. Fill in the blank spaces:
    (a) All mammals (except a few) have _____ cervical vertebra.
    (b) The number of phalanges in each limb of human is _____
    (c) Thin filament of myofibril contains 2 'F' actins and two other proteins namely _____ and _____.
    (d) In a muscle fibre Ca^{++} is stored in _____
    (e) _____ and _____ pairs of ribs are called floating ribs.
    (f) The human cranium is made of _____ bones.

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Chapter 18
Neural Control and Coordination

18.1 *Neural System*

18.2 *Human Neural System*

18.3 *Neuron as Structural and Functional Unit of Neural System*

18.4 *Central Neural System*

As you know, the functions of the organs/organ systems in our body must be coordinated to maintain homeostasis. **Coordination** is the process through which two or more organs interact and complement the functions of one another. For example, when we do physical exercises, the energy demand is increased for maintaining an increased muscular activity. The supply of oxygen is also increased. The increased supply of oxygen necessitates an increase in the rate of respiration, heart beat and increased blood flow via blood vessels. When physical exercise is stopped, the activities of nerves, lungs, heart and kidney gradually return to their normal conditions. Thus, the functions of muscles, lungs, heart, blood vessels, kidney and other organs are coordinated while performing physical exercises. In our body the neural system and the endocrine system jointly coordinate and integrate all the activities of the organs so that they function in a synchronised fashion.

The neural system provides an organised network of point-to-point connections for a quick coordination. The endocrine system provides chemical integration through hormones. In this chapter, you will learn about the neural system of human, mechanisms of neural coordination like transmission of nerve impulse and impulse conduction across a synapse.

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18.1 NEURAL SYSTEM

The neural system of all animals is composed of highly specialised cells called **neurons** which can detect, receive and transmit different kinds of stimuli.

The neural organisation is very simple in lower invertebrates. For example, in *Hydra* it is composed of a network of neurons. The neural system is better organised in insects, where a brain is present along with a number of ganglia and neural tissues. The vertebrates have a more developed neural system.

18.2 HUMAN NEURAL SYSTEM

The human neural system is divided into two parts :

(i) the **central neural system** (CNS)

(ii) the **peripheral neural system** (PNS)

The CNS includes the **brain** and the **spinal cord** and is the site of information processing and control. The PNS comprises of all the nerves of the body associated with the CNS (brain and spinal cord). The nerve fibres of the PNS are of two types :

(a) **afferent fibres**

(b) **efferent fibres**

The afferent nerve fibres transmit impulses from tissues/organs to the CNS and the efferent fibres transmit regulatory impulses from the CNS to the concerned peripheral tissues/organs.

The PNS is divided into two divisions called **somatic neural system** and **autonomic neural system**. The somatic neural system relays impulses from the CNS to skeletal muscles while the autonomic neural system transmits impulses from the CNS to the involuntary organs and smooth muscles of the body. The autonomic neural system is further classified into **sympathetic neural system** and **parasympathetic neural system**.

Visceral nervous system is the part of the peripheral nervous system that comprises the whole complex of nerves, fibres, ganglia, and plexuses by which impulses travel from the central nervous system to the viscera and from the viscera to the central nervous system.

18.3 NEURON AS STRUCTURAL AND FUNCTIONAL UNIT OF NEURAL SYSTEM

A neuron is a microscopic structure composed of three major parts, namely, **cell body**, **dendrites** and **axon** (Figure 18.1). The cell body contains cytoplasm with typical cell organelles and certain granular bodies called **Nissl's granules**. Short fibres which branch repeatedly and project out of the cell body also

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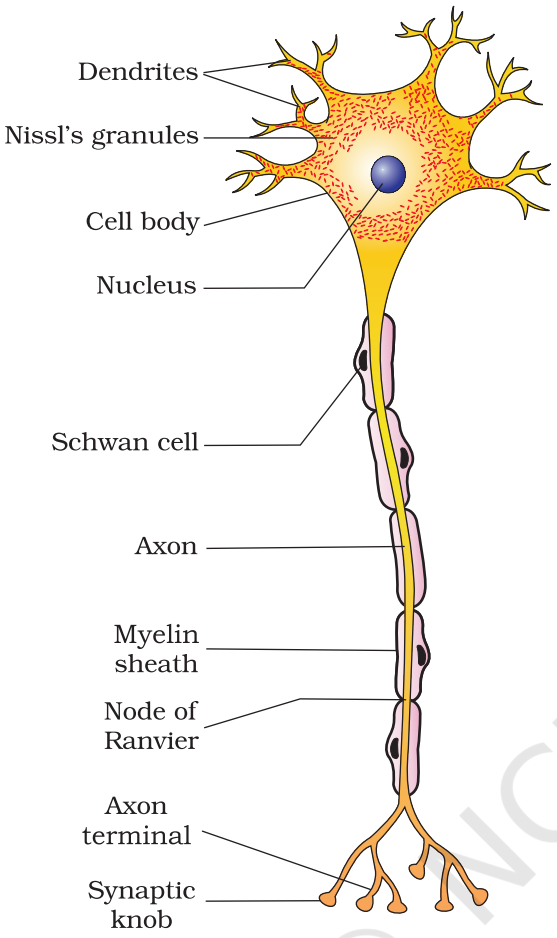

Figure 18.1 Structure of a neuron

contain Nissl's granules and are called dendrites. These fibres transmit impulses towards the cell body. The axon is a long fibre, the distal end of which is branched. Each branch terminates as a bulb-like structure called **synaptic knob** which possess synaptic vesicles containing chemicals called **neurotransmitters**. The axons transmit nerve impulses away from the cell body to a synapse or to a neuro-muscular junction. Based on the number of axon and dendrites, the neurons are divided into three types, i.e., **multipolar** (with one axon and two or more dendrites; found in the cerebral cortex), **bipolar** (with one axon and one dendrite, found in the retina of eye) and **unipolar** (cell body with one axon only; found usually in the embryonic stage). There are two types of axons, namely, **myelinated** and **non-myelinated**. The myelinated nerve fibres are enveloped with **Schwann cells,** which form a myelin sheath around the axon. The gaps between two adjacent myelin sheaths are called **nodes of Ranvier**. Myelinated nerve fibres are found in spinal and cranial nerves. Unmyelinated nerve fibre is enclosed by a Schwann cell that does not form a myelin sheath around the axon, and is commonly found in autonomous and the somatic neural systems.

18.3.1 Generation and Conduction of Nerve Impulse

Neurons are excitable cells because their membranes are in a polarised state. *Do you know why the membrane of a neuron is polarised?* Different types of ion channels are present on the neural membrane. These ion channels are selectively permeable to different ions. When a neuron is not conducting any impulse, i.e., resting, the axonal membrane is comparatively more permeable to potassium ions (K^+) and nearly impermeable to sodium ions (Na^+). Similarly, the membrane is impermeable to negatively charged proteins present in the axoplasm. Consequently, the axoplasm inside the axon contains high concentration of K^+ and negatively charged proteins and low concentration of Na^+. In contrast, the fluid outside the axon contains a low concentration of K^+, a high concentration of Na^+ and thus form a concentration gradient. These ionic gradients across the resting membrane are maintained by the active transport of ions by the sodium-potassium pump which transports 3 Na^+ outwards for 2 K^+ into the cell. As a result, the outer surface of the axonal membrane possesses a positive charge while its inner surface

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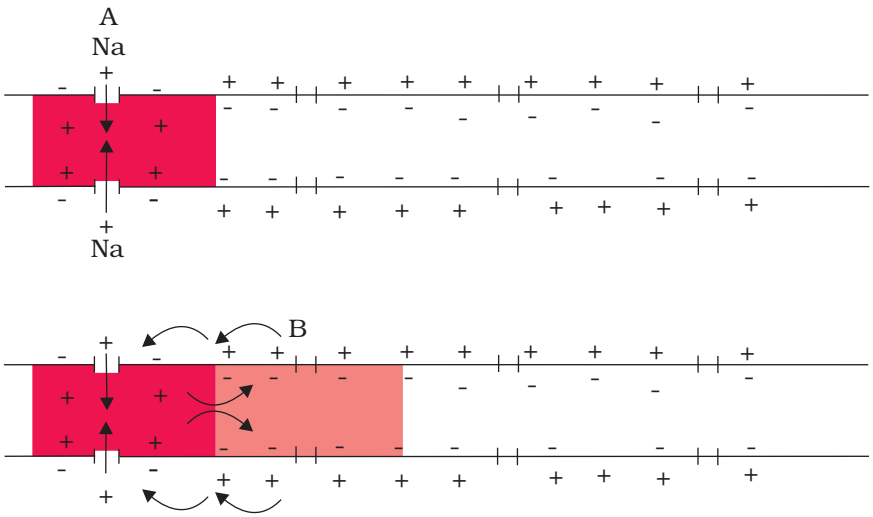

Figure 18.2 Diagrammatic representation of impulse conduction through an axon (at points A and B)

becomes negatively charged and, therefore is, polarised. The electrical potential difference across the resting plasma membrane is called as the **resting potential**.

You might be curious to know about the mechanisms of generation of nerve impulse and its conduction along an axon. When a stimulus is applied at a site (Figure 18.2 e.g., point A) on the polarised membrane, the membrane at the site A becomes freely permeable to Na^+. This leads to a rapid influx of Na^+ followed by the reversal of the polarity at that site, i.e., the outer surface of the membrane becomes negatively charged and the inner side becomes positively charged. The polarity of the membrane at the site A is thus reversed and hence depolarised. The electrical potential difference across the plasma membrane at the site A is called the **action potential**, which is in fact termed as a **nerve impulse**. At sites immediately ahead, the axon (e.g., site B) membrane has a positive charge on the outer surface and a negative charge on its inner surface. As a result, a current flows on the inner surface from site A to site B. On the outer surface current flows from site B to site A (Figure 18.2) to complete the circuit of current flow. Hence, the polarity at the site is reversed, and an action potential is generated at site B. Thus, the **impulse** (action potential) generated at site A arrives at site B. The sequence is repeated along the length of the axon and consequently the impulse is conducted. The rise in the stimulus-induced permeability to Na^+ is extremely short-lived. It is quickly followed by a rise in permeability to K^+. Within a fraction of a second, K^+ diffuses outside the membrane and restores the resting potential of the membrane at the site of excitation and the fibre becomes once more responsive to further stimulation.

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18.3.2 Transmission of Impulses

A nerve impulse is transmitted from one neuron to another through junctions called synapses. A **synapse** is formed by the membranes of a pre-synaptic neuron and a post-synaptic neuron, which may or may not be separated by a gap called **synaptic cleft**. There are two types of synapses, namely, electrical synapses and chemical synapses. At electrical synapses, the membranes of pre- and post-synaptic neurons are in very close proximity. Electrical current can flow directly from one neuron into the other across these synapses. Transmission of an impulse across electrical synapses is very similar to impulse conduction along a single axon. Impulse transmission across an electrical synapse is always faster than that across a chemical synapse. Electrical synapses are rare in our system.

At a chemical synapse, the membranes of the pre- and post-synaptic neurons are separated by a fluid-filled space called synaptic cleft (Figure 18.3). *Do you know how the pre-synaptic neuron transmits an impulse (action potential) across the synaptic cleft to the post-synaptic neuron*? Chemicals called neurotransmitters are involved in the transmission of impulses at these synapses. The axon terminals contain vesicles filled with these neurotransmitters. When an impulse (action potential) arrives at the axon terminal, it stimulates the movement of the synaptic vesicles towards the membrane where they fuse with the plasma

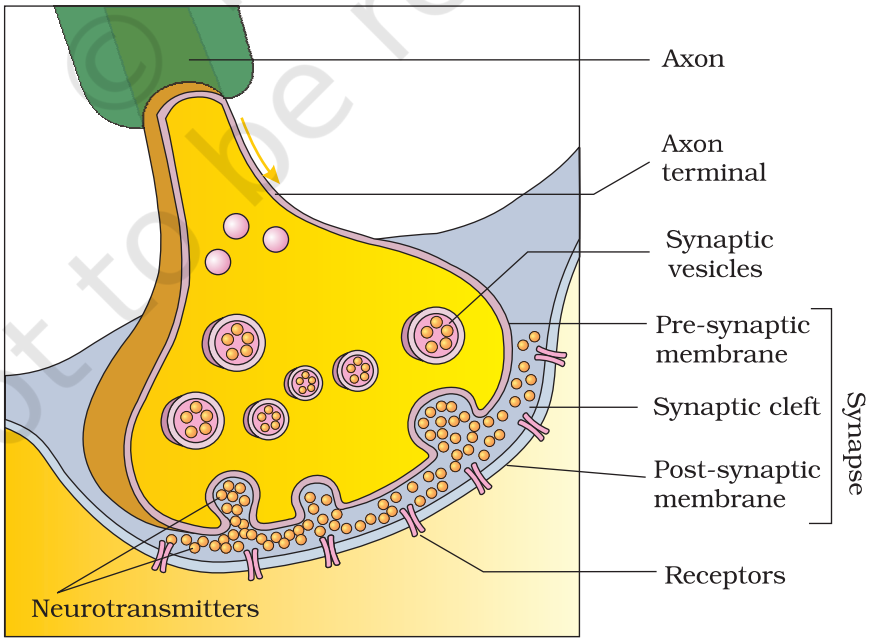

Figure 18.3 Diagram showing axon terminal and synapse

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membrane and release their neurotransmitters in the synaptic cleft. The released neurotransmitters bind to their specific **receptors**, present on the post-synaptic membrane. This binding opens ion channels allowing the entry of ions which can generate a new potential in the post-synaptic neuron. The new potential developed may be either excitatory or inhibitory.

18.4 CENTRAL NEURAL SYSTEM

The brain is the central information processing organ of our body, and acts as the 'command and control system'. It controls the voluntary movements, balance of the body, functioning of vital involuntary organs (e.g., lungs, heart, kidneys, etc.), thermoregulation, hunger and thirst, circadian (24-hour) rhythms of our body, activities of several endocrine glands and human behaviour. It is also the site for processing of vision, hearing, speech, memory, intelligence, emotions and thoughts.

The human brain is well protected by the skull. Inside the skull, the brain is covered by **cranial meninges** consisting of an outer layer called **dura mater**, a very thin middle layer called **arachnoid** and an inner layer (which is in contact with the brain tissue) called **pia mater**. The brain can be divided into three major parts: (i) **forebrain**, (ii) **midbrain**, and (iii) **hindbrain** (Figure 18.4).

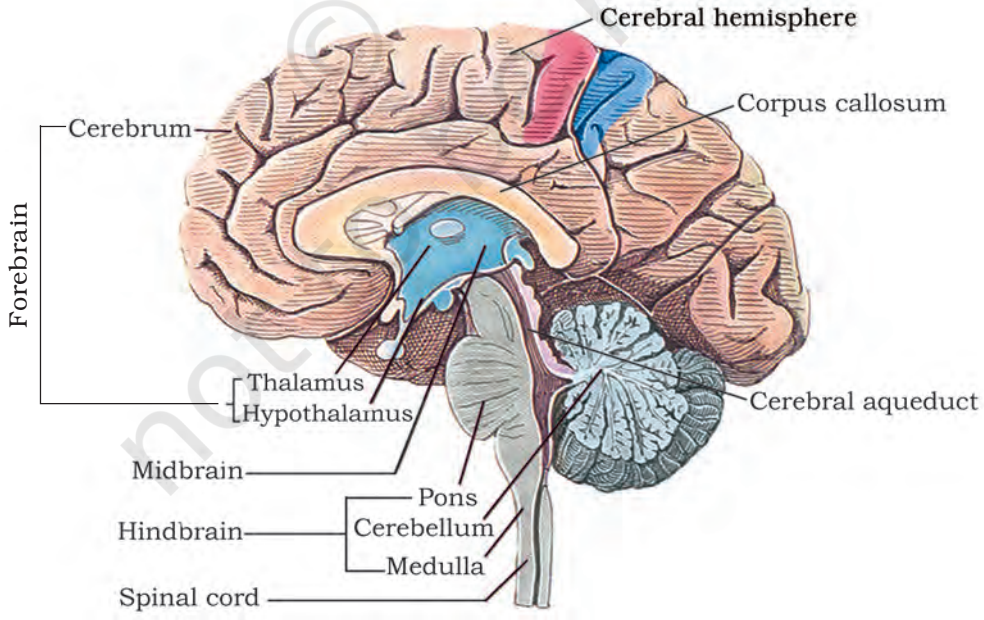

Figure 18.4 Diagram showing sagital section of the human brain

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18.4.1 Forebrain

The forebrain consists of **cerebrum**, **thalamus** and **hypothalamus** (Figure 18.4). Cerebrum forms the major part of the human brain. A deep cleft divides the cerebrum longitudinally into two halves, which are termed as the left and right **cerebral hemispheres**. The hemispheres are connected by a tract of nerve fibres called **corpus callosum**. The layer of cells which covers the cerebral hemisphere is called cerebral cortex and is thrown into prominent folds. The cerebral cortex is referred to as the grey matter due to its greyish appearance. The neuron cell bodies are concentrated here giving the colour. The cerebral cortex contains motor areas, sensory areas and large regions that are neither clearly sensory nor motor in function. These regions called as the **association areas** are responsible for complex functions like intersensory associations, memory and communication. Fibres of the tracts are covered with the myelin sheath, which constitute the inner part of cerebral hemisphere. They give an opaque white appearance to the layer and, hence, is called the white matter. The cerebrum wraps around a structure called thalamus, which is a major coordinating centre for sensory and motor signaling. Another very important part of the brain called **hypothalamus** lies at the base of the thalamus. The hypothalamus contains a number of centres which control body temperature, urge for eating and drinking. It also contains several groups of neurosecretory cells, which secrete hormones called hypothalamic hormones. The inner parts of cerebral hemispheres and a group of associated deep structures like amygdala, hippocampus, etc., form a complex structure called the limbic lobe or limbic system. Along with the hypothalamus, it is involved in the regulation of sexual behaviour, expression of emotional reactions (e.g., excitement, pleasure, rage and fear), and motivation.

18.4.2 Midbrain

The midbrain is located between the thalamus/hypothalamus of the forebrain and pons of the hindbrain. A canal called the **cerebral aqueduct** passess through the midbrain. The dorsal portion of the midbrain consists mainly of four round swellings (lobes) called **corpora quadrigemina**.

18.4.3 Hindbrain

The hindbrain comprises **pons**, **cerebellum** and **medulla** (also called the medulla oblongata). Pons consists of fibre tracts that interconnect different regions of the brain. Cerebellum has very convoluted surface in order to provide the additional space for many more neurons. The medulla of the brain is connected to the spinal cord. The medulla contains centres which control respiration, cardiovascular reflexes and gastric secretions.

Three major regions make up the brain stem; mid brain, pons and medulla oblongata. Brain stem forms the connections between the brain and spinal cord.

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SUMMARY

The neural system coordinates and integrates functions as well as metabolic and homeostatic activities of all the organs. Neurons, the functional units of neural system are excitable cells due to a differential concentration gradient of ions across the membrane. The electrical potential difference across the resting neural membrane is called the 'resting potential'. The nerve impulse is conducted along the axon membrane in the form of a wave of depolarisation and repolarisation. A synapse is formed by the membranes of a pre-synaptic neuron and a post-synaptic neuron which may or may not be separated by a gap called synaptic cleft. Chemicals involved in the transmission of impulses at chemical synapses are called neurotransmitters.

Human neural system consists of two parts : (i) central neural system (CNS) and (ii) the peripheral neural system. The CNS consists of the brain and spiral cord. The brain can be divided into three major parts : (i) forebrain, (ii) midbrain and (iii) hindbrain. The forebrain consists of cerebrum, thalamus and hypothalamus. The cerebrum is longitudinally divided into two halves that are connected by the corpus callosum. A very important part of the forebrain called hypothalamus controls the body temperature, eating and drinking. Inner parts of cerebral hemispheres and a group of associated deep structures form a complex structure called limbic system which is concerned with olfaction, autonomic responses, regulation of sexual behaviour, expression of emotional reactions, and motivation. The midbrain receives and integrates visual, tactile and auditory inputs. The hindbrain comprises pons, cerebellum and medulla. The cerebellum integrates information received from the semicircular canals of the ear and the auditory system. The medulla contains centres, which control respiration, cardiovascular reflexes, and gastric secretions. Pons consist of fibre tracts that interconnect different regions of the brain.

EXERCISES

1. Briefly describe the structure of the Brain
2. Compare the following:
   (a) Central neural system (CNS) and Peripheral neural system (PNS)
   (b) Resting potential and action potential
3. Explain the following processes:
   (a) Polarisation of the membrane of a nerve fibre
   (b) Depolarisation of the membrane of a nerve fibre
   (c) Transmission of a nerve impulse across a chemical synapse

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4. Draw labelled diagrams of the following:
   (a) Neuron (b) Brain
5. Write short notes on the following:
   (a) Neural coordination (b) Forebrain (c) Midbrain
   (d) Hindbrain (e) Synapse
6. Give a brief account of Mechanism of synaptic transmission.
7. Explain the role of Na^+ in the generation of action potential.
8. Differentiate between:
   (a) Myelinated and non-myelinated axons
   (b) Dendrites and axons
   (c) Thalamus and Hypothalamus
   (d) Cerebrum and Cerebellum
9. Answer the following:
   (a) Which part of the human brain is the most developed?
   (b) Which part of our central neural system acts as a master clock?
10. Distinguish between:
   (a) afferent neurons and efferent neurons
   (b) impulse conduction in a myelinated nerve fibre and unmyelinated nerve fibre
   (f) cranial nerves and spinal nerves.

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Chapter 19
Chemical Coordination and Integration

19.1 *Endocrine Glands and Hormones*

19.2 *Human Endocrine System*

19.3 *Hormones of Heart, Kidney and Gastrointestinal Tract*

19.4 *Mechanism of Hormone Action*

You have already learnt that the neural system provides a point-to-point rapid coordination among organs. The neural coordination is fast but short-lived. As the nerve fibres do not innervate all cells of the body and the cellular functions need to be continuously regulated; a special kind of coordination and integration has to be provided. This function is carried out by hormones. The neural system and the endocrine system jointly coordinate and regulate the physiological functions in the body.

19.1 Endocrine Glands and Hormones

Endocrine glands lack ducts and are hence, called ductless glands. Their secretions are called hormones. The classical definition of hormone as a chemical produced by endocrine glands and released into the blood and transported to a distantly located target organ has current scientific definition as follows: **Hormones are non-nutrient chemicals which act as intercellular messengers and are produced in trace amounts**. The new definition covers a number of new molecules in addition to the hormones secreted by the organised endocrine glands. Invertebrates possess very simple endocrine systems with few hormones whereas a large number of chemicals act as hormones and provide coordination in the vertebrates. The human endocrine system is described here.

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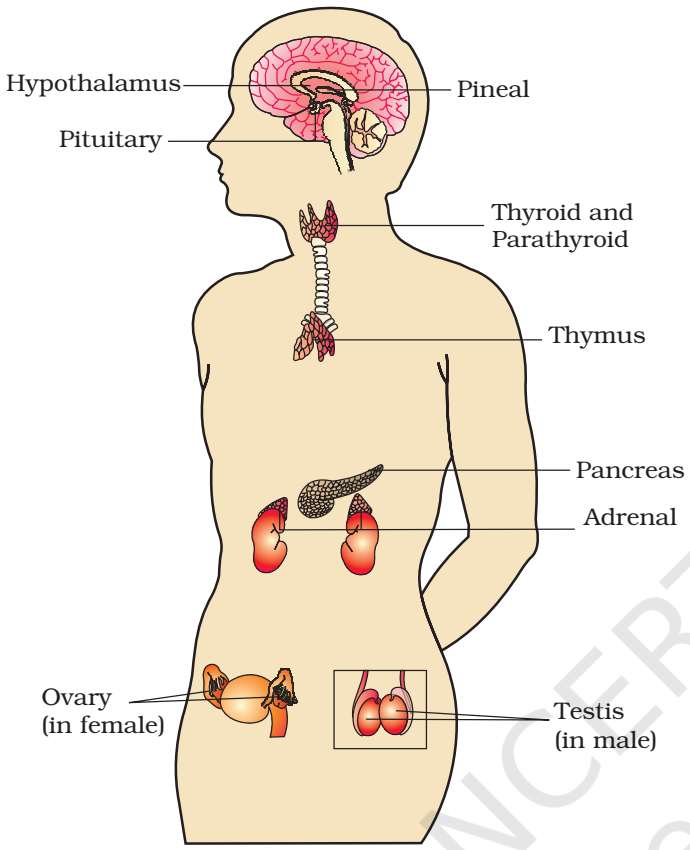

Figure 19.1 Location of endocrine glands

19.2 HUMAN ENDOCRINE SYSTEM

The endocrine glands and hormone producing diffused tissues/cells located in different parts of our body constitute the endocrine system. Pituitary, pineal, thyroid, adrenal, pancreas, parathyroid, thymus and gonads (testis in males and ovary in females) are the organised endocrine bodies in our body (Figure 19.1). In addition to these, some other organs, e.g., gastrointestinal tract, liver, kidney, heart also produce hormones. A brief account of the structure and functions of all major endocrine glands and hypothalamus of the human body is given in the following sections.

19.2.1 The Hypothalamus

As you know, the hypothalamus is the basal part of diencephalon, forebrain (Figure 19.1) and it regulates a wide spectrum of body functions. It contains several groups of neurosecretory cells called nuclei which produce hormones. These hormones regulate the synthesis and secretion of pituitary hormones. However, the hormones produced by hypothalamus are of two types, the releasing hormones (which stimulate secretion of pituitary hormones) and the inhibiting hormones (which inhibit secretions of pituitary hormones). For example a hypothalamic hormone called Gonadotrophin releasing hormone (GnRH) stimulates the pituitary synthesis and release of gonadotrophins. On the other hand, somatostatin from the hypothalamus inhibits the release of growth hormone from the pituitary. These hormones originating in the hypothalamic neurons, pass through axons and are released from their nerve endings. These hormones reach the pituitary gland through a portal circulatory system and regulate the functions of the anterior pituitary. The posterior pituitary is under the direct neural regulation of the hypothalamus (Figure 19.2).

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19.2.2 The Pituitary Gland

The pituitary gland is located in a bony cavity called sella tursica and is attached to hypothalamus by a stalk (Figure 19.2). It is divided anatomically into an **adenohypophysis** and a **neurohypophysis**. Adenohypophysis consists of two portions, pars distalis and pars intermedia. The pars distalis region of pituitary, commonly called anterior pituitary, produces **growth hormone** (GH), **prolactin** (PRL), **thyroid stimulating hormone** (TSH), **adrenocorticotrophic hormone** (ACTH), **luteinizing hormone** (LH) and **follicle stimulating hormone** (FSH). Pars intermedia secretes only one hormone called **melanocyte stimulating hormone** (MSH). However, in humans, the pars intermedia is almost merged with pars distalis. Neurohypophysis (pars nervosa) also known as posterior pituitary, stores and releases two hormones called **oxytocin** and **vasopressin,** which are actually synthesised by the hypothalamus and are transported axonally to neurohypophysis.

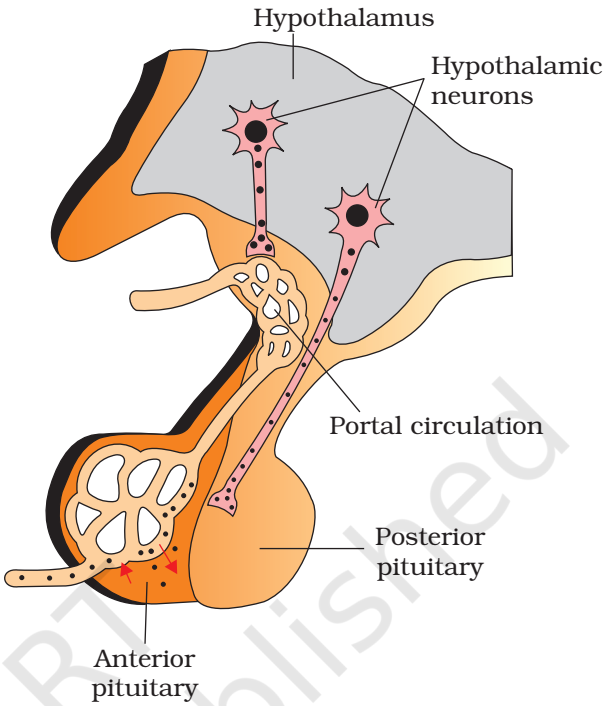

Figure 19.2 Diagrammatic representation of pituitary and its relationship with hypothalamus

Over-secretion of GH stimulates abnormal growth of the body leading to gigantism and low secretion of GH results in stunted growth resulting in pituitary dwarfism. Excess secretion of growth hormone in adults especially in middle age can result in severe disfigurement (especially of the face) called **Acromegaly**, which may lead to serious complications, and premature death if unchecked. The disease is hard to diagnose in the early stages and often goes undetected for many years, until changes in external features become noticeable. Prolactin regulates the growth of the mammary glands and formation of milk in them. TSH stimulates the synthesis and secretion of thyroid hormones from the thyroid gland. ACTH stimulates the synthesis and secretion of steroid hormones called **glucocorticoids** from the adrenal cortex. LH and FSH stimulate gonadal activity and hence are called **gonadotrophins**. In males, LH stimulates the synthesis and secretion of hormones called **androgens** from testis. In males, FSH and androgens regulate spermatogenesis. In females, LH induces ovulation of fully mature follicles (graafian follicles) and maintains the corpus luteum, formed from the remnants of the graafian follicles after ovulation. FSH stimulates growth and development of the ovarian

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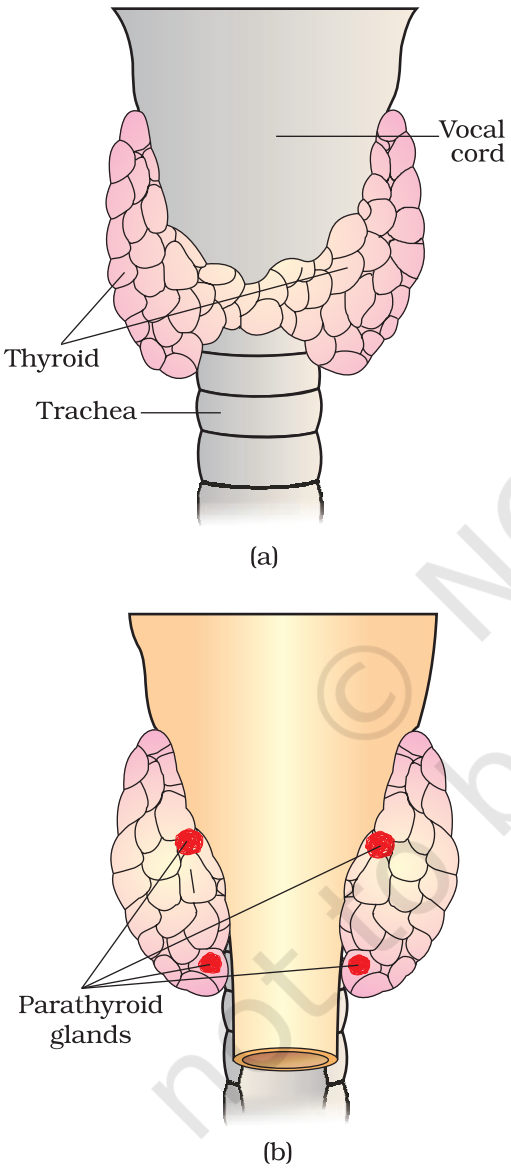

Figure 19.3 Diagrammatic view of the position of Thyroid and Parathyroid
(a) Ventral side
(b) Dorsal side

follicles in females. MSH acts on the melanocytes (melanin containing cells) and regulates pigmentation of the skin. Oxytocin acts on the smooth muscles of our body and stimulates their contraction. In females, it stimulates a vigorous contraction of uterus at the time of child birth, and milk ejection from the mammary gland. Vasopressin acts mainly at the kidney and stimulates resorption of water and electrolytes by the distal tubules and thereby reduces loss of water through urine (diuresis). Hence, it is also called as **anti-diuretic hormone** (ADH).

An impairment affecting synthesis or release of ADH results in a diminished ability of the kidney to conserve water leading to water loss and dehydration. This condition is known as **Diabetes Insipidus**.

19.2.3 The Pineal Gland

The pineal gland is located on the dorsal side of forebrain. Pineal secretes a hormone called **melatonin**. Melatonin plays a very important role in the regulation of a 24-hour (diurnal) rhythm of our body. For example, it helps in maintaining the normal rhythms of sleep-wake cycle, body temperature. In addition, melatonin also influences metabolism, pigmentation, the menstrual cycle as well as our defense capability.

19.2.4 Thyroid Gland

The thyroid gland is composed of two lobes which are located on either side of the trachea (Figure 19.3 a). Both the lobes are interconnected with a thin flap of connective tissue called isthmus. The thyroid gland is composed of **follicles** and **stromal tissues**. Each thyroid follicle is composed of follicular cells, enclosing a cavity. These follicular cells synthesise two hormones, **tetraiodothyronine** or **thyroxine** (T_4) and **triiodothyronine** (T_3). Iodine is essential for the normal rate of hormone synthesis in the thyroid. Deficiency of iodine in our diet results in **hypothyroidism** and enlargement of the thyroid gland, commonly called **goitre**. Hypothyroidism during pregnancy causes defective development and maturation of the growing baby leading to stunted growth (cretinism), mental

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retardation, low intelligence quotient, abnormal skin, deaf-mutism, etc. In adult women, hypothyroidism may cause menstrual cycle to become irregular. Due to cancer of the thyroid gland or due to development of nodules of the thyroid glands, the rate of synthesis and secretion of the thyroid hormones is increased to abnormal high levels leading to a condition called **hyperthyroidism** which adversely affects the body physiology.

Exopthalmic goitre is a form of hyperthyroidism, characterised by enlargement of the thyroid gland, protrusion of the eyeballs, increased basal metabolic rate, and weight loss, also called **Graves' disease.**

Thyroid hormones play an important role in the regulation of the basal metabolic rate. These hormones also support the process of red blood cell formation. Thyroid hormones control the metabolism of carbohydrates, proteins and fats. Maintenance of water and electrolyte balance is also influenced by thyroid hormones. Thyroid gland also secretes a protein hormone called thyrocalcitonin (TCT) which regulates the blood calcium levels.

19.2.5 Parathyroid Gland

In humans, four parathyroid glands are present on the back side of the thyroid gland, one pair each in the two lobes of the thyroid gland (Figure 19.3 b). The parathyroid glands secrete a peptide hormone called **parathyroid hormone** (PTH). The secretion of PTH is regulated by the circulating levels of calcium ions.

Parathyroid hormone (PTH) increases the Ca^{2+} levels in the blood. PTH acts on bones and stimulates the process of bone resorption (dissolution/ demineralisation). PTH also stimulates reabsorption of Ca^{2+} by the renal tubules and increases Ca^{2+} absorption from the digested food. It is, thus, clear that PTH is a hypercalcemic hormone, i.e., it increases the blood Ca^{2+} levels. Along with TCT, it plays a significant role in calcium balance in the body.

19.2.6 Thymus

The thymus gland is a lobular structure located between lungs behind sternum on the ventral side of aorta. The thymus plays a major role in the development of the immune system. This gland secretes the peptide hormones called **thymosins**. Thymosins play a major role in the differentiation of **T-lymphocytes**, which provide **cell-mediated immunity**. In addition, thymosins also promote production of antibodies to provide **humoral immunity**. Thymus is degenerated in old individuals resulting in a decreased production of thymosins. As a result, the immune responses of old persons become weak.

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19.2.7 Adrenal Gland

Our body has one pair of adrenal glands, one above of each kidney (Figure 19.4 a). The gland is composed of two types of tissues. The centrally located tissue is called the **adrenal medulla**, *and outside this lies the* **adrenal cortex** *(Figure 19.4 b).*

Underproduction of hormones by the adrenal cortex alters carbohydrate metabolism causing acute weakness and fatigue leading to a disease called **Addison's disease**.

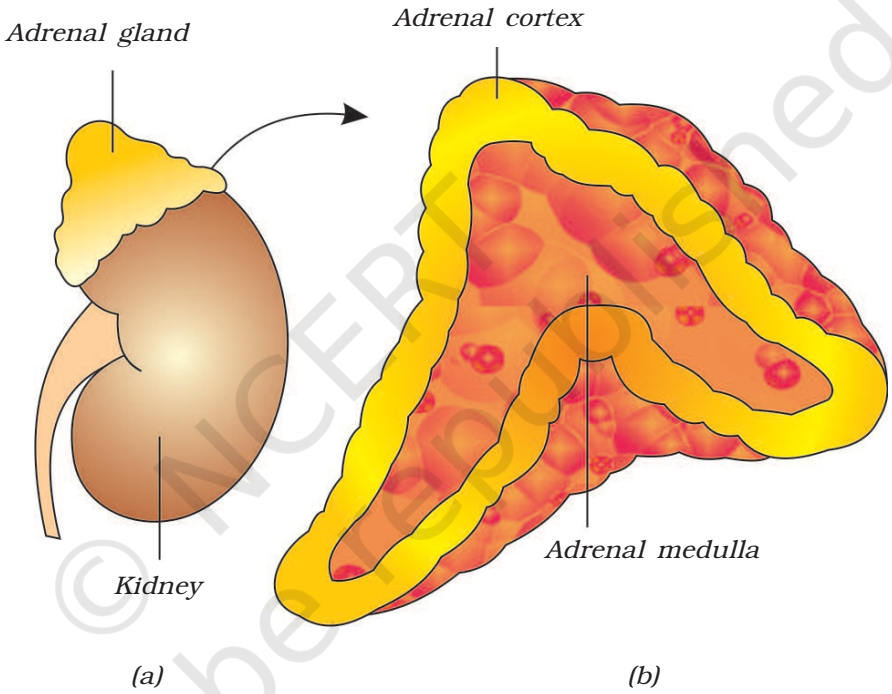

Figure 19.4 *Diagrammatic representation of : (a) Adrenal gland above kidney (b) Section showing two parts of adrenal gland*

The adrenal medulla secretes two hormones called **adrenaline** *or* **epinephrine** *and* **noradrenaline** *or* **norepinephrine**. *These are commonly called as* **catecholamines**. *Adrenaline and noradrenaline are rapidly secreted in response to stress of any kind and during emergency situations and are called* **emergency hormones** *or* **hormones of Fight or Flight**. *These hormones increase alertness, pupilary dilation, piloerection (raising of hairs), sweating etc. Both the hormones increase the heart beat, the strength of heart contraction and the rate of respiration. Catecholamines also stimulate the breakdown of glycogen resulting in*

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an increased concentration of glucose in blood. In addition, they also stimulate the breakdown of lipids and proteins.

The adrenal cortex can be divided into three layers, called **zona reticularis** (inner layer), **zona fasciculata** (middle layer) and **zona glomerulosa** (outer layer). The adrenal cortex secretes many hormones, commonly called as **corticoids**. The corticoids, which are involved in carbohydrate metabolism are called glucocorticoids. In our body, cortisol is the main glucocorticoid. Corticoids, which regulate the balance of water and electrolytes in our body are called mineralocorticoids. Aldosterone is the main mineralocorticoid in our body.

Glucocorticoids stimulate gluconeogenesis, lipolysis and proteolysis; and inhibit cellular uptake and utilisation of amino acids. Cortisol is also involved in maintaining the cardio-vascular system as well as the kidney functions. Glucocorticoids, particularly cortisol, produces anti-inflammatory reactions and suppresses the immune response. Cortisol stimulates the RBC production. Aldosterone acts mainly at the renal tubules and stimulates the reabsorption of Na^+ and water and excretion of K^+ and phosphate ions. Thus, aldosterone helps in the maintenance of electrolytes, body fluid volume, osmotic pressure and blood pressure. Small amounts of androgenic steroids are also secreted by the adrenal cortex which play a role in the growth of axial hair, pubic hair and facial hair during puberty.

19.2.8 Pancreas

Pancreas is a composite gland (Figure 19.1) which acts as both exocrine and endocrine gland. The endocrine pancreas consists of 'Islets of Langerhans'. There are about 1 to 2 million Islets of Langerhans in a normal human pancreas representing only 1 to 2 per cent of the pancreatic tissue. The two main types of cells in the Islet of Langerhans are called **α-cells** and **β-cells**. The α-cells secrete a hormone called **glucagon**, while the **β**-cells secrete **insulin**.

Glucagon is a peptide hormone, and plays an important role in maintaining the normal blood glucose levels. Glucagon acts mainly on the liver cells (hepatocytes) and stimulates glycogenolysis resulting in an increased blood sugar (**hyperglycemia**). In addition, this hormone stimulates the process of gluconeogenesis which also contributes to hyperglycemia. Glucagon reduces the cellular glucose uptake and utilisation. Thus, glucagon is a **hyperglycemic hormone**.

Insulin is a peptide hormone, which plays a major role in the regulation of glucose homeostasis. Insulin acts mainly on hepatocytes and adipocytes (cells of adipose tissue), and enhances cellular glucose

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uptake and utilisation. As a result, there is a rapid movement of glucose from blood to hepatocytes and adipocytes resulting in decreased blood glucose levels (**hypoglycemia**). Insulin also stimulates conversion of glucose to glycogen (**glycogenesis**) in the target cells. The glucose homeostasis in blood is thus maintained jointly by the two – insulin and glucagons.

Prolonged hyperglycemia leads to a complex disorder called **diabetes mellitus** which is associated with loss of glucose through urine and formation of harmful compounds known as ketone bodies. Diabetic patients are successfully treated with insulin therapy.

19.2.9 Testis

A pair of testis is present in the scrotal sac (outside abdomen) of male individuals (Figure 19.1). Testis performs dual functions as a primary sex organ as well as an endocrine gland. Testis is composed of **seminiferous tubules** and **stromal or interstitial tissue.** The **Leydig cells** or **interstitial cells**, which are present in the intertubular spaces produce a group of hormones called **androgens** mainly **testosterone.**

Androgens regulate the development, maturation and functions of the male accessory sex organs like epididymis, vas deferens, seminal vesicles, prostate gland, urethra etc. These hormones stimulate muscular growth, growth of facial and axillary hair, aggressiveness, low pitch of voice etc. Androgens play a major stimulatory role in the process of spermatogenesis (formation of spermatozoa). Androgens act on the central neural system and influence the male sexual behaviour (libido). These hormones produce anabolic (synthetic) effects on protein and carbohydrate metabolism.

19.2.10 Ovary

Females have a pair of ovaries located in the abdomen (Figure 19.1). Ovary is the primary female sex organ which produces one ovum during each menstrual cycle. In addition, ovary also produces two groups of steroid hormones called **estrogen** and **progesterone**. Ovary is composed of ovarian follicles and stromal tissues. The estrogen is synthesised and secreted mainly by the growing ovarian follicles. After ovulation, the ruptured follicle is converted to a structure called **corpus luteum**, which secretes mainly **progesterone**.

Estrogens produce wide ranging actions such as stimulation of growth and activities of female secondary sex organs, development of growing

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ovarian follicles, appearance of female secondary sex characters (e.g., high pitch of voice, etc.) and mammary gland development. Estrogens also regulate female sexual behaviour.

Progesterone supports pregnancy. Progesterone also acts on the mammary glands and stimulates the formation of alveoli (sac-like structures which store milk) and milk secretion.

19.3 HORMONES OF HEART, KIDNEY AND GASTROINTESTINAL TRACT

Now you know about the endocrine glands and their hormones. However, as mentioned earlier, hormones are also secreted by some tissues which are not endocrine glands. For example, the atrial wall of our heart secretes a very important peptide hormone called **atrial natriuretic factor** (ANF), which decreases blood pressure. When blood pressure is increased, ANF is secreted which causes dilation of the blood vessels. This reduces the blood pressure.

The juxtaglomerular cells of kidney produce a peptide hormone called **erythropoietin** which stimulates erythropoiesis (formation of RBC).

Endocrine cells present in different parts of the gastro-intestinal tract secrete four major peptide hormones, namely **gastrin**, **secretin**, **cholecystokinin** (CCK) and **gastric inhibitory peptide** (GIP). Gastrin acts on the gastric glands and stimulates the secretion of hydrochloric acid and pepsinogen. Secretin acts on the exocrine pancreas and stimulates secretion of water and bicarbonate ions. CCK acts on both pancreas and gall bladder and stimulates the secretion of pancreatic enzymes and bile juice, respectively. GIP inhibits gastric secretion and motility. Several other non-endocrine tissues secrete hormones called **growth factors.** These factors are essential for the normal growth of tissues and their repairing/regeneration.

19.4 MECHANISM OF HORMONE ACTION

Hormones produce their effects on target tissues by binding to specific proteins called **hormone receptors** located in the target tissues only. Hormone receptors present on the cell membrane of the target cells are called membrane-bound receptors and the receptors present inside the target cell are called intracellular receptors, mostly nuclear receptors (present in the nucleus). Binding of a hormone to its receptor leads to the formation of a **hormone-receptor complex** (Figure 19.5 a, b). Each receptor is specific to one hormone only and hence receptors are specific. Hormone-Receptor complex formation leads to certain biochemical changes in the target tissue. Target tissue metabolism and hence

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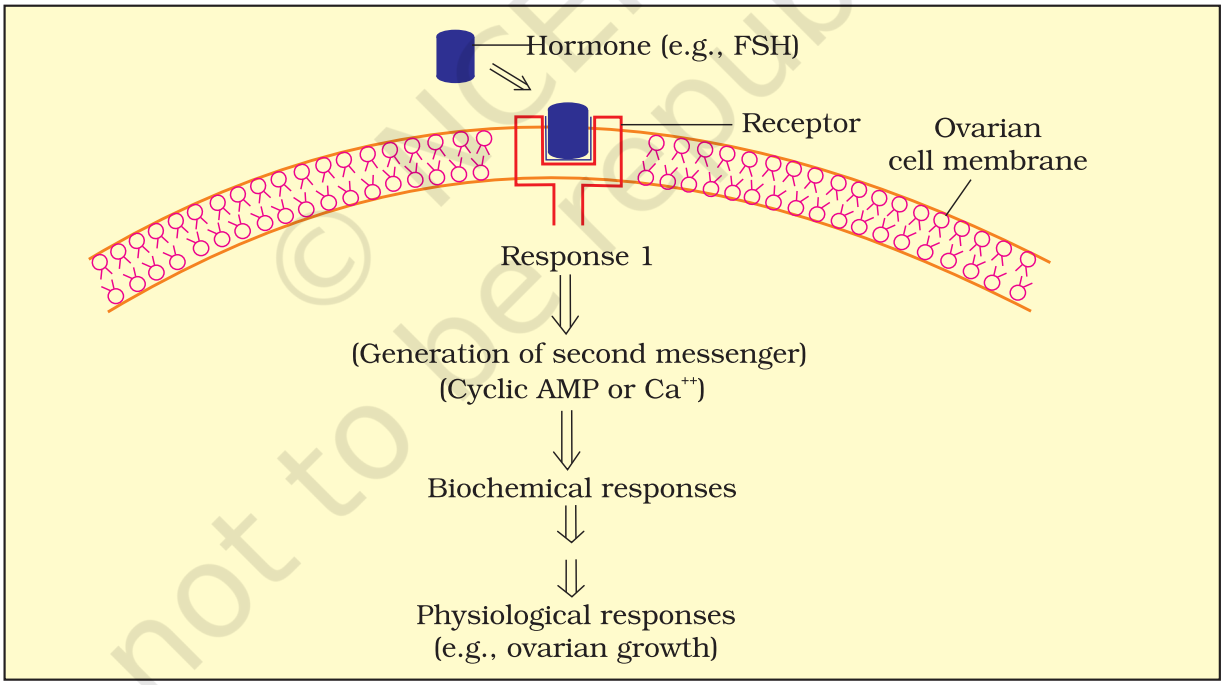
physiological functions are regulated by hormones. On the basis of their chemical nature, hormones can be divided into groups :

(i) **peptide, polypeptide, protein hormones** (e.g., insulin, glucagon, pituitary hormones, hypothalamic hormones, etc.)
(ii) **steroids** (e.g., cortisol, testosterone, estradiol and progesterone)
(iii) **iodothyronines** (thyroid hormones)
(iv) **amino-acid derivatives** (e.g., epinephrine).

Hormones which interact with membrane-bound receptors normally do not enter the target cell, but generate second messengers (e.g., cyclic AMP, IP_3, Ca^{++} etc) which in turn regulate cellular metabolism (Figure 19.5a). Hormones which interact with intracellular receptors (e.g., steroid hormones, iodothyronines, etc.) mostly regulate gene expression or chromosome function by the interaction of hormone-receptor complex with the genome. Cumulative biochemical actions result in physiological and developmental effects (Figure 19.5b).



(a)

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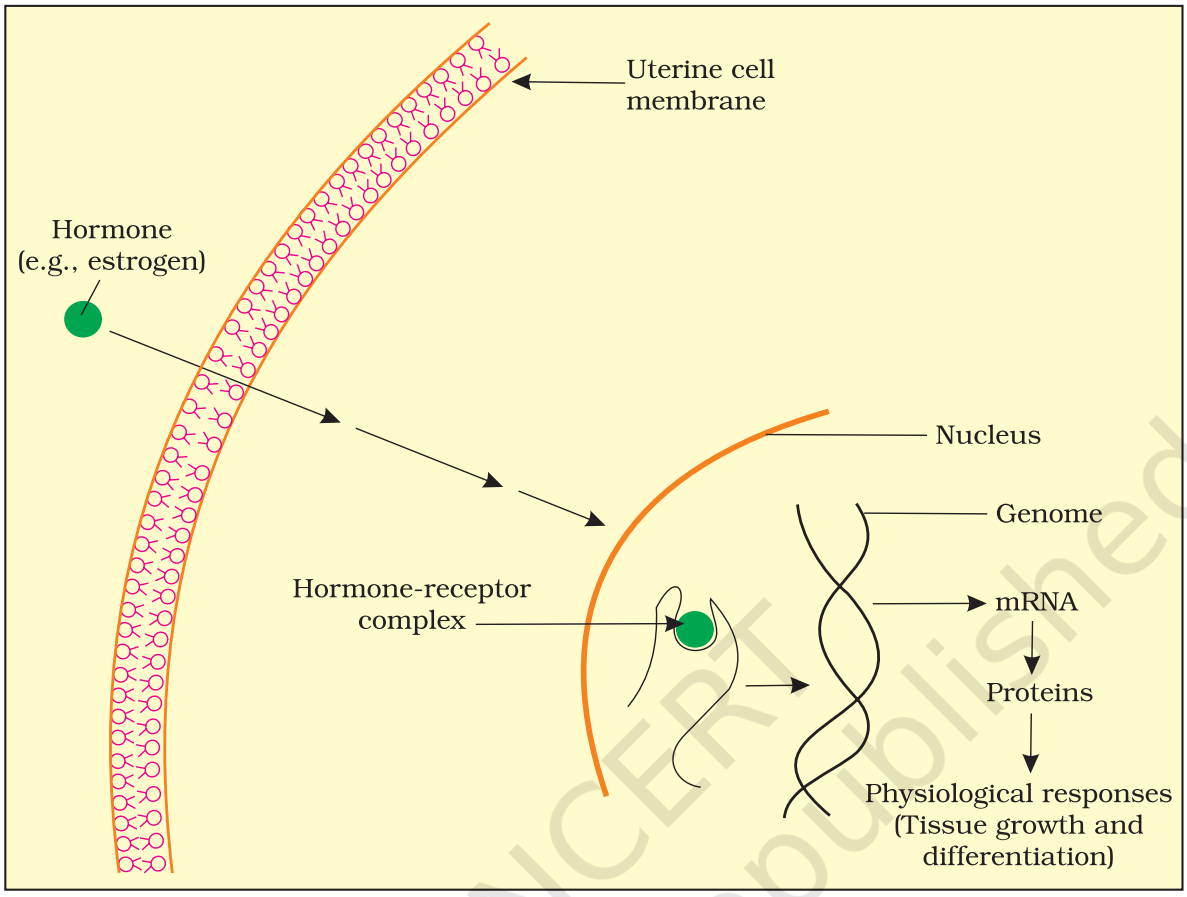

Figure 19.5 Diagramatic representation of the mechanism of hormone action : (a) Protein hormone (b) Steroid hormone

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SUMMARY

There are special chemicals which act as hormones and provide chemical coordination, integration and regulation in the human body. These hormones regulate metabolism, growth and development of our organs, the endocrine glands or certain cells. The endocrine system is composed of hypothalamus, pituitary and pineal, thyroid, adrenal, pancreas, parathyroid, thymus and gonads (testis and ovary). In addition to these, some other organs, e.g., gastrointestinal tract, kidney, heart etc., also produce hormones. The pituitary gland is divided into three major parts, which are called as pars distalis, pars intermedia and pars nervosa. Pars distalis produces six trophic hormones. Pars intermedia secretes

only one hormone, while pars nervosa (neurohypophysis) secretes two hormones. The pituitary hormones regulate the growth and development of somatic tissues and activities of peripheral endocrine glands. Pineal gland secretes melatonin, which plays a very important role in the regulation of 24-hour (diurnal) rhythms of our body (e.g., rhythms of sleep and state of being awake, body temperature, etc.). The thyroid gland hormones play an important role in the regulation of the basal metabolic rate, development and maturation of the central neural system, erythropoiesis, metabolism of carbohydrates, proteins and fats, menstrual cycle. Another thyroid hormone, i.e., thyrocalcitonin regulates calcium levels in our blood by decreasing it. The parathyroid glands secrete parathyroid hormone (PTH) which increases the blood Ca^{2+} levels and plays a major role in calcium homeostasis. The thymus gland secretes thymosins which play a major role in the differentiation of T-lymphocytes, which provide cell-mediated immunity. In addition, thymosins also increase the production of antibodies to provide humoral immunity. The adrenal gland is composed of the centrally located adrenal medulla and the outer adrenal cortex. The adrenal medulla secretes epinephrine and norepinephrine. These hormones increase alertness, pupilary dilation, piloerection, sweating, heart beat, strength of heart contraction, rate of respiration, glycogenolysis, lipolysis, proteolysis. The adrenal cortex secretes glucocorticoids and mineralocorticoids. Glucocorticoids stimulate gluconeogenesis, lipolysis, proteolysis, erythropoiesis, cardio-vascular system, blood pressure, and glomerular filtration rate and inhibit inflammatory reactions by suppressing the immune response. Mineralocorticoids regulate water and electrolyte contents of the body. The endocrine pancreas secretes glucagon and insulin. Glucagon stimulates glycogenolysis and gluconeogenesis resulting in hyperglycemia. Insulin stimulates cellular glucose uptake and utilisation, and glycogenesis resulting in hypoglycemia. Insulin deficiency and/or insulin resistance result in a disease called diabetes mellitus.

The testis secretes androgens, which stimulate the development, maturation and functions of the male accessory sex organs, appearance of the male secondary sex characters, spermatogenesis, male sexual behaviour, anabolic pathways and erythropoiesis. The ovary secretes estrogen and progesterone. Estrogen stimulates growth and development of female accessory sex organs and secondary sex characters. Progesterone plays a major role in the maintenance of pregnancy as well as in mammary gland development and lactation. The atrial wall of the heart produces atrial natriuretic factor which decreases the blood pressure. Kidney produces erythropoietin which stimulates erythropoiesis. The gastrointestinal tract secretes gastrin, secretin, cholecystokinin and gastric inhibitory peptide. These hormones regulate the secretion of digestive juices and help in digestion.

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EXERCISES

1. Define the following:
   (a) Exocrine gland
   (b) Endocrine gland
   (c) Hormone
2. Diagrammatically indicate the location of the various endocrine glands in our body.
3. List the hormones secreted by the following:

(a) Hypothalamus	(b) Pituitary	(c) Thyroid	(d) Parathyroid
(e) Adrenal	(f) Pancreas	(g) Testis	(h) Ovary
(i) Thymus	(j) Atrium	(k) Kidney	(l) G-I Tract

4. Fill in the blanks:

Hormones	**Target gland**
(a) Hypothalamic hormones	_____
(b) Thyrotrophin (TSH)	_____
(c) Corticotrophin (ACTH)	_____
(d) Gonadotrophins (LH, FSH)	_____
(e) Melanotrophin (MSH)	_____

5. Write short notes on the functions of the following hormones:
   (a) Parathyroid hormone (PTH) (b) Thyroid hormones
   (c) Thymosins (d) Androgens
   (e) Estrogens (f) Insulin and Glucagon
6. Give example(s) of:
   (a) Hyperglycemic hormone and hypoglycemic hormone
   (b) Hypercalcemic hormone
   (c) Gonadotrophic hormones
   (d) Progestational hormone
   (e) Blood pressure lowering hormone
   (f) Androgens and estrogens
7. Which hormonal deficiency is responsible for the following:
   (a) Diabetes mellitus (b) Goitre (c) Cretinism
8. Briefly mention the mechanism of action of FSH.
9. Match the following:

Column I	**Column II**
(a) T_4	(i) Hypothalamus
(b) PTH	(ii) Thyroid
(c) GnRH	(iii) Pituitary
(d) LH	(iv) Parathyroid

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NOTE

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